Hydrogen from Renewables: Blowing Away The Myths

Now with 2018 Data

Assessing the Viability of Zero Emissions Hydrogen with Real World Data from Fuel Suppliers and Vehicle Manufacturers

First a Note on Range and Emissions Tests

In this presentation I use two different sets of figures from car manufacturers:

1. EPA: This is the American fuel economy and range test that is widely acknowledged to give closer to real-world data. I use this wherever possible and especially where it is important to have real numbers, such as when calculating how many cars the national grid can support.

2. NEDC: This is the European fuel economy and range test that is widely acknowledged to give numbers that are fantasy and near impossible to achieve without driving unrealistically slowly. It is discredited and is being phased out in favour of the WLTP test. However at this time all manufacturers are still quoting NEDC figures and hence is the only way to give a like-for-like comparison between cars with different fuel types.

OK? Right, let's start…

The Hydrogen Dream – Clean, Zero Emissions, Free Fuel

"One of the ways to make sure that we become fully less dependent on oil is through hydrogen. And we are spending $1.2 billion to encourage hydrogen fuel cells. It's coming, it's coming. It's an interesting industry evolution, to think about your automobiles being powered by hydrogen, and the only emission is water vapor." - *George W Bush, 2006*

"The route between ITM Power's latest hydrogen refueling stations shows how commercial fleets can operate within and around central London without compromise. This enables London and further cities to meet their business, climate and air quality emissions and presents a solution for improving air quality in direct competition to the incumbent diesel powered vehicles". – *Arcola Energy, 2016*

"BOC is proud to continue to work with ITM Power in the development of a hydrogen refueling network in the UK. This is the third deployment of our innovative refueling station technology with ITM Power this year, with the installation at CEME another milestone in making hydrogen a truly accessible clean fuel in and around London". – *BOC, 2016*

"CEME is very proud to be able to offer a site for this hydrogen fuel station and utilise our solar energy to make a fuel for vehicles. It is perfectly located to offer a clean hydrogen source for London and improve air quality for London" – *CEME, 2016*

Hydrogen is a versatile, clean, and safe energy carrier that can be used as fuel for power or in industry as feedstock, as well as it can be easily stored on large scale. Hydrogen Council members are committed to promoting its deployment. Hydrogen can be produced from (renewable) electricity and from carbon-abated fossil fuels and produces zero emissions at point of use." – *Hydrogen Council, 2017*

Sounds too good to be true, doesn't it?

2001 - From Hydrogen Enthusiast…

“Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable … water will be the coal of the future.” *– Jules Verne, 1874, The Mysterious Island*

In 2001 I very much believed the layman’s view:

- Hydrogen is space age technology
- Gives zero emissions
- Gives fast fill-ups
- Is the most abundant element in the universe
- Cars like the BMW 750h and 2001 Mini-h will soon be in your local dealer

TV shows like “Top Gear” have reinforced this impression, and 15 years later many people still believe it without question (for example, see letters pages of car magazines, internet forums, etc).

> “…the first car driven by a child born today could be powered by hydrogen, and pollution-free.” *– G W Bush, 2003, announcing hydrogen fuel initiative to put hydrogen cars on the road by 2010*

After all, the only emissions are water, *right*?

2001 BMW Hydrogen Mini

Shell hydrogen pump, LA

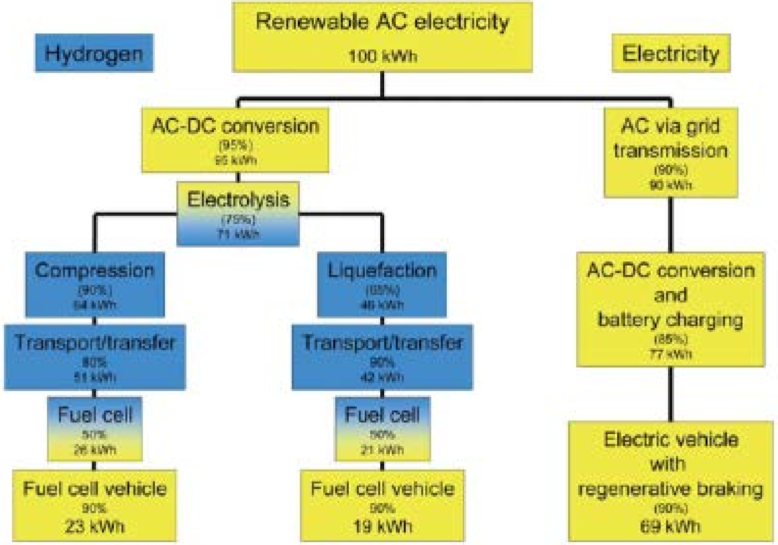
…to Hydrogen Sceptic

But wait! Why the voices of dissent?

"Hydrogen can be shown to be nonsense with basic high school math" – *internet posting, circa 2004*

"Hydrogen cars are a poor short-term strategy, and it's not even clear that they are a good idea in the long term" – *Professor Alex Farrell, assistant professor of energy and resources at UC Berkeley, 2003*

"The answer is that there is a political hoax underway today in America—and that lazy journalists risk falling victim to it." – *Unraveling the Great Hydrogen Hoax, 2004, Nieman Reports*



Bossel, 2006 [1]

Energy losses through different paths from source to vehicle

[1] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4016414

2006 IEEE Paper from Dr Ulf Bossel of the European Fuel Cell Forum

INVITED PAPER

Proceedings of the IEEE
October 2006

Does a Hydrogen Economy Make Sense?

Electricity obtained from hydrogen fuel cells appears to be four times as expensive as electricity drawn from the electrical transmission grid.

By Ulf Bossel

ABSTRACT | The establishment of a sustainable energy future is one of the most pressing tasks of mankind. With the exhaustion of fossil resources the energy economy will change from a chemical to an electrical base. This transition is one of physics, not one of politics. It must be based on proven technology and existing engineering experience. The transition process will take many years and should start soon. Unfortunately, politics seems to listen to the advice of visionaries and lobby groups. Many of their qualitative arguments are not based on facts and physics. A secure sustainable energy future cannot be based on hype and activism, but has to be built on solid grounds of established science and engineering. In this paper the energy needs of a hydrogen economy are quantified. Only 20%–25% of the source energy needed to synthesized hydrogen from natural compounds can be recovered for end use by efficient fuel cells. Because of the high energy losses within a hydrogen economy the synthetic energy carrier cannot compete with electricity. As the fundamental laws of physics cannot be chanced by research, politics or investments, a hydrogen economy will never make sense.

KEYWORDS | Electrolysis; electron economy; energy; energy efficiency; heating values; heat of formation; hydrogen; hydrogen compression; hydrogen economy; hydrogen liquefaction; hydrogen pipelines; hydrogen storage; hydrogen transfer; hydrogen transport; metal hydrides; onsite hydrogen generation; reforming

I. INTRODUCTION

The technology needed to establish a hydrogen economy is available or can be developed. Two comprehensive 2004 studies by the U.S. National Research Council [1] and the American Physical Society [2] summarize technical options and identify needs for further improvements. They are concerned with the cost of hydrogen obtained from various sources, but fail to address the key question of the overall energy balance of a hydrogen economy. Energy is needed to synthesize hydrogen and to deliver it to the user, and energy is lost when the gas is converted back to electricity by fuel cells. How much energy is needed to liberate hydrogen from water by electrolysis or high-temperature thermodynamics or by chemistry? Where does the energy come from and in which form is it harvested? Do we have enough clean water for electrolysis and steam reforming? How and where do we safely deposit the enormous amounts of carbon dioxide if hydrogen is derived from coal?

This paper extends a previous analysis of the parasitic energy needs of a hydrogen economy [3]. It argues that the energy problem cannot be solved in a sustainable way by introducing hydrogen as an energy carrier. Instead, energy from renewable sources and high energy efficiency between source and service will become the key points of a sustainable solution. The establishment of an efficient "electron economy" appears to be more appropriate than the creation of a much less efficient "hydrogen economy."

II. THE CHALLENGE

The following examples illustrate the nature of the challenge involved in creating a hydrogen economy.

It takes about 1 kg of hydrogen to replace 1 U.S. gal of gasoline. About 200 MJ (55 kWh) of dc electricity are needed to liberate 1 kg of hydrogen from 9 kg of water by electrolysis. Steam reforming of methane (natural gas) requires only 4.5 kg of water for each kilogram of hydrogen, but 5.5 kg of CO_2 emerge from the process. One kilogram of hydrogen can also be obtained from 3 kg of coal and 9 kg of water, but 11 kg of CO_2 are released and need to be sequestered. Even with most efficient fuel cell systems, at most 50% of the hydrogen HHV energy can be converted back to electricity.

- It takes 55 kWh of electricity to create 1 kg of hydrogen from 9 kg of water by electrolysis [1]
- Alternately, best case steam reforming of natural gas produces 5.5 kg of CO2 per 1 kg of hydrogen

- To quote the author:
  - 'About four renewable power plants have to be erected to deliver the output of one plant ... Three of these plants generate energy to cover the parasitic losses of the hydrogen economy while only one of them is producing useful energy'
  - 'As the fundamental laws of physics cannot be changed by research, politics or investments, a hydrogen economy will never make sense'
  - 'The title question "Does a hydrogen economy make sense?" must be answered with a definite "Never"'

[1] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4016414

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0018-9219/$20.00 ©2006 IEEE

- Criticisms levied at the paper:
  - It was written in 2006 and is obsolete
  - It ignores the overall efficiency of the vehicle the drivetrain is installed into
  - It uses (actually consistently correctly) Higher Heating Value and not Lower Heating Value for hydrogen

Practical Examples: Data from Real World Scenarios

2012 Real World Figures: Hydrogen Filling Station

Motoring journalist Quentin Willson refuelling the Hyundai ix35 Fuel cell car with HFuel at Nottingham University

Bexi81 - Wikimedia

- HFuel 100: 100 kg / day capacity electrolyser with 75+% efficiency [1]
- 60 kWh / kg hydrogen system efficiency [1]
- Cost £713,243 plus 5% p.a. maintenance [1]

[1] http://www.itm-power.com/news-item/update-on-hydrogen-cost-structure

2016 Real World Figures: M1 Wind Powered Filling Station

James Wingrove

Rotherham Wind Hydrogen Fuel Station

- Wind powered site at Rotherham near M1 with ITM Power 270 kW electrolyser
- 225 kW Vestas V29 wind turbine
- Findings from operational data: [1]
  - 52 kWh / kg needed to create hydrogen from water (agrees with use of HHV at 76% efficiency)
  - 10.2 kWh / kg to pump and store hydrogen to 350 bar, with peak compressor power of 45 kW
    - ➢ Total electricity needed for upgraded 700 bar operation is higher, but not published. Theoretically it is 30% higher (i.e. 13 kWh). I will conservatively use the value for 350 bar here.
  - Total electricity use (for 350 bar operation) **62.2 kWh / kg**, giving 63% system efficiency
    - ➢ This number is for near Beginning of Life: End of Life electricity use is up to 25% higher[2].

[1] *Optimal operation of a hydrogen refuelling station combined with wind power in the electricity market, Carr et al, International Journal of Hydrogen Energy Volume 41, Issue 46, 14 December 2016, Pages 21057–21066* http://dx.doi.org/10.1016/j.ijhydene.2016.09.073

[2] *High Pressure Hydrogen All Electrochemical Decentralized Refueling Station* http://www.fch.europa.eu/project/high-pressure-hydrogen-all-electrochemical-decentralized-refueling-station

Real World Figures: Toyota Mirai

Toyota Mirai
Fully Charged

- Range specification:
  - 312 miles (EPA) [1]
  - 550 km (NEDC) [2]
- Hydrogen capacity: 5 kg at 700 bar pressure
- EPA range per kg: 62.4 miles
- Average range measured by Autocar: 45 miles per kg [3]
- 4 seat hatchback
- Top speed 111 mph, 0-60 mph in 9.6 seconds
- On the road price of £65,220 [4,5]

[1] https://www.toyota.co.uk/world-of-toyota/stories-news-events/mirai-goes-the-extra-mile.json
[2] https://www.toyota-europe.com/download/cms/euen/Toyota%20Mirai%20FCV_Posters_LR_tcm-11-564265.pdf
[3] http://www.autocar.co.uk/car-review/toyota/mirai/mpg
[4] https://www.intelligentcarleasing.com/deals/toyota/mirai
[5] https://www.autocar.co.uk/car-review/toyota/mirai/specs

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- EPA range per kg: 62.4 miles
- Average range measured by Autocar: 45 miles per kg [3]

- Electricity to produce and store hydrogen: 62.2 kWh/kg
  - Electricity for one tank: 311 kWh
- Upstream electricity / mile = 1 kWh (EPA)
- Upstream electricity / km = 565 Wh (NEDC)

This is over 3x the electricity consumption of a similar sized EV!

[1] https://www.toyota.co.uk/world-of-toyota/stories-news-events/mirai-goes-the-extra-mile.json
[2] https://www.toyota-europe.com/download/cms/euen/Toyota%20Mirai%20FCV_Posters_LR_tcm-11-564265.pdf
[3] http://www.autocar.co.uk/car-review/toyota/mirai/mpg

“But it’s renewable, so it’s ok…”

James Wingrove

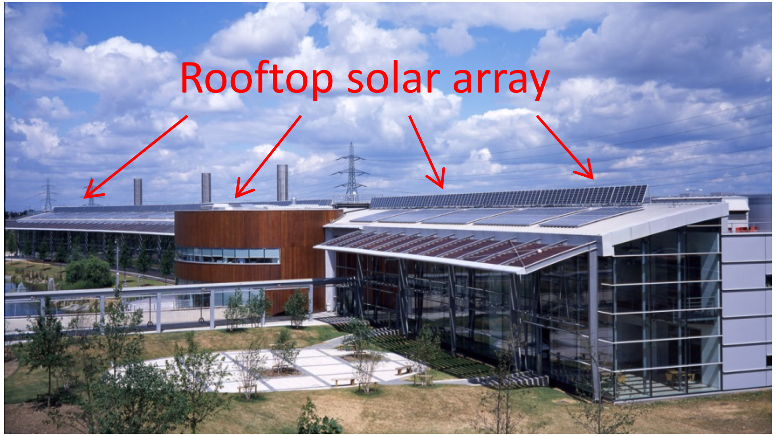
Rotherham Wind Hydrogen Fuel Station

- Rotherham wind to hydrogen fuelling station
  – 225 kW wind turbine feeding;
  – 270 kW electrolyser
- Average hub wind speed at site [1] : 5.4 m/s
- Average daily production [2] : 1078 kWh
  – Which makes: 17.3 kg hydrogen
- Storage for 21 days

Average number of cars that can fill up per day: 3.5

[1] http://www.rensmart.com/Weather/BERR
[2] http://gebrauchtewindkraftanlagen.com/files/brands/40/vestas_6.pdf

“But it’s renewable, so it’s ok…”



CEME Conference Centre with 115 kWp solar array, near A13, East London

- A13 Solar hydrogen fuelling station
  - Full roof 115 kWp solar array [1]
- Average daily production in July:
  - 410 kWh [2]
  - 6.6 kg hydrogen
  - 1.3 cars
- Average daily production in December:
  - 106 kWh [2]
  - 1.7 kg hydrogen
  - 0.3 cars

Average number of cars that can fill up per day, over the year: 0.9

[1] http://www.itm-power.com/news-item/agreement-to-deploy-a-solar-hydrogen-refuelling-station-on-the-a13
[2] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#

Scaling to Fully Commercial Operations

Building a 200 kg per day Hydrogen Filling Station

- Numerous projects are now targeting 200+ kg hydrogen production per day[1,2]
- Larger PEM electrolysers are optimised for throughput and lower capex and not efficiency [3]. However energy is saved by new electrochemical compressor technologies [4]. 200kg/day leads to system efficiencies of:
  - Beginning of life efficiency: 75% [1]
  - End of life (~7 years) efficiency: 62%
- This in turn leads to upstream electricity use of :
  - Beginning of life: 57.9 kWh / kg [4]
  - End of life: 81.7 kWh / kg
  - Average over life of equipment: **69.8 kWh / kg**
- **349 kWh** now needed to generate 5kg of hydrogen for the Toyota Mirai and similar cars

This compares to 65-68 kWh / kg system BoL efficiency stated by Hydrogenics [5]

[1] *PHAEDRUS: ADVANCED REFUELLING PROJECT* http://www.itm-power.com/news-item/phaedrus-advanced-refuelling-project

[2] https://www.hydrogenics.com/2018/10/15/hydrogenics-to-supply-large-scale-pem-electrolyzer-for-hydrogen-fueling-station-in-europe/

[3] *Future cost and performance of water electrolysis: An expert elicitation study* https://www.sciencedirect.com/science/article/pii/S0360319917339435#bib56

[4] *High Pressure Hydrogen All Electrochemical Decentralized Refueling Station* http://www.fch.europa.eu/project/high-pressure-hydrogen-all-electrochemical-decentralized-refueling-station

[5] http://www.hydrogenics.com/wp-content/uploads/Renewable-Hydrogen-Brochure.pdf

How practical is a full size hydrogen filling station?

- The average supermarket filling station today dispenses 11 million litres of fuel per year [1]
  - 30,000 litres per day
- Taking current UK fleet fuel economy, that is 300,000 miles sold per day
  - Requires approximately 5000 kg of hydrogen from 330,000 kWh of electricity and 100,000 litres of water
- To enable a wind powered filling station, each site requires 49 MW of wind turbines
  - Average UK onshore wind capacity factor is 28% [2] (*assuming for these examples that this applies at any location)*
- Typical modern onshore wind turbine is 2 to 3 MW but the largest are now 4.2 MW
  - Enercon E-126: Hub height 159 metres, diameter 127 metres

Therefore 12 of the largest onshore turbines needed for one filling station

[1] http://www.ukpia.com/docs/default-source/default-document-library/statistical-review-2016.pdf?sfvrsn=0
[2] https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes

How practical is a full size hydrogen filling station?

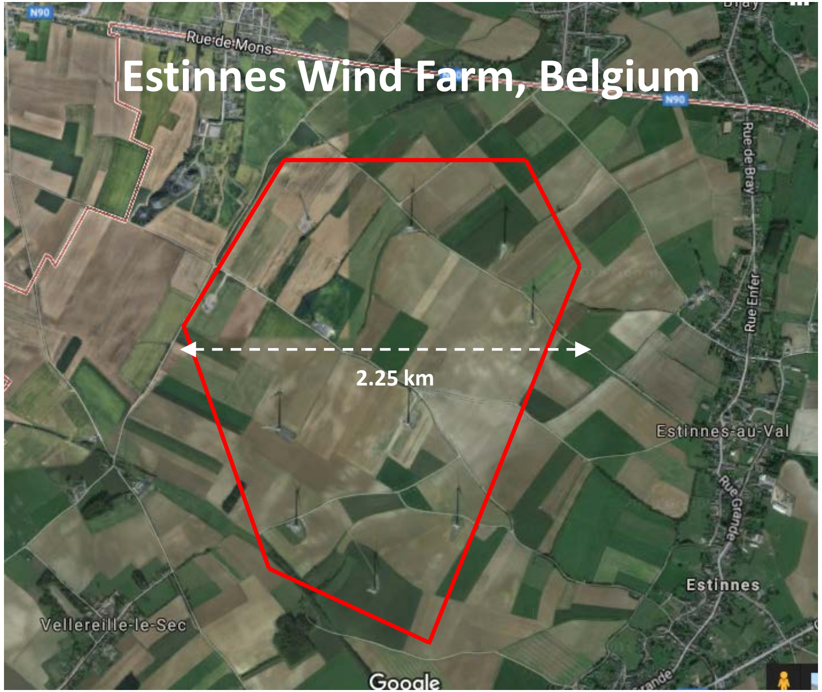
Left: 11 Enercon E-126 turbines at Estinnes, Belgium.

Below: Size of the E-126 relative to various London landmarks. With a maximum blade height of 222.5 metres, the turbine is 31.5 metres higher than the tip of the BT tower antenna and it has a diameter equivalent to the London Eye.

How practical is a full size hydrogen filling station?

Left: Bray village in foreground and wind farm behind, from 5 km. Right: Some of the E-126 turbines in the wind farm behind the town of Binche, from 6 km. It is clearly not practical to consider siting these turbines alongside a hydrogen filling station in an urban setting.

How practical is a full size hydrogen filling station?



The boundaries of the Estinnes wind farm transposed onto Winchester at same scale. Note the 8 main petrol stations. The marked area would not supply the needs of 1 supermarket filling station.

How practical is it to convert the UK to hydrogen?

- There were 8494 filling stations in the UK dispensing 55.2 billion litres of fuel in 2015
  - 151 million litres per day
- Taking average UK fleet fuel economy, that is 1.5 billion miles sold per day
  - Requires almost 21.5 million kg of hydrogen
  - Requires approximately 1.5 billion kWh of electricity
- Requires approximately 225,000 MWp of wind turbines
  - This is roughly 4 times the current total peak demand on the UK grid
  - This is more than 10 times the current total peak output of all UK onshore and off-shore wind turbines
  - Again, assumes average UK onshore wind capacity factor is 28%

53,000 of the largest on-shore 4.2 MW turbines needed, covering an area larger than Wales

When Renewables are Not Optimally Located: Green Park, Reading

Andrew Smith - Geograph

Period	Capacity (MW)	Load Factor	MWh
2005/2006	2	10.10%	1,767
2006/2007	2	18.70%	3,283
2007/2008	2	18.50%	3,254
2008/2009	2	16.20%	2,837
2009/2010	2	15.40%	2,692
2010/2011	2	13.10%	2,297
2011/2012	2	15.00%	2,641
2012/2013	2	16.50%	2,892
2013/2014	2	19.20%	3,371
2014/2015	2	15.10%	2,639
2015/2016	2	19.20%	3,370
Rolling Load Factor		16.40%	

Renewable Energy Foundation

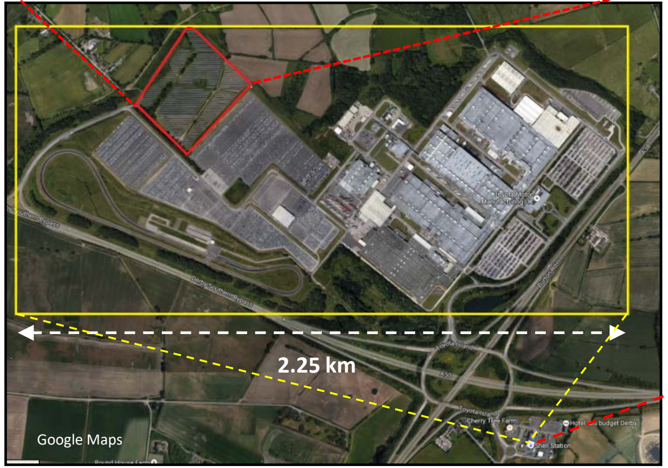
- 2 MW turbine adjacent to the M4, powering an office park and EV charging facility
- Typical of many of the sites one could expect for a supermarket filling station
- Average load factor over life of turbine:

  16.4%

Shows the 28% figure used so far is likely to be highly optimistic!

What about generating hydrogen with solar?


Toyota UK Flickr: Toyota Solar Panel Array



Google Maps

- A supermarket-equivalent sized filling station (bottom of satellite photo) at the Toyota factory in Derby would need:
  - 127 MWp solar array with 500,000 panels
  - 280 hectares of solar panels (yellow boundary)
  - 300 tonnes of hydrogen storage for winter use (assuming no boil-off)
- Size of whole Toyota factory site: 235 hectares [1]
  - Toyota's existing array (one of UK's biggest) is 4.1 MWp (**red boundary**) [2]


Google Streetview

[1] http://news.bbc.co.uk/2/hi/programmes/working_lunch/education/180422
[2] http://www.toyotauk.com/environment/renewable-energy.html

The land take for a single full off-grid, renewables-powered filling station (equivalent to an average supermarket filling station) is enormous and does not realistically scale to practical throughputs

Supermarket and petrol station sites are usually not optimal for locating renewables

The reality is that any such commercial-scale filling station would have to be grid connected…

OK – so if we have to use the grid…

- A supermarket replacement hydrogen filling station would need:
  - Approximately 330,000 kWh of electricity per day
  - 12,500 kWh per hour
  - 13 MW grid connection
- 2017-18 UK grid emissions were 225 g CO2 per kWh [1]
  - Transmission losses were 12%
  - Onsite hydrogen production gives 17.59 kg_{CO2} /kg_{H2}
- Toyota Mirai upstream CO2 emissions in UK: 160 g / km (NEDC)
  - Toyota's widely used EPA equivalent gives 282 g / mile

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/737451/fuel-mix-disclosure-data-2018-revised-2.pdf

Comparison with Battery Electric Vehicles

Real World Figures: Hyundai Kona EV

The Hyundai Kona Electric is the first 'mass market' electric car with a range of over 250 miles in the UK. Its 64 kWh battery is mounted in the floor, giving a full 5 seat cabin.

Hyundai Kona Electric

- Range estimation: 258 miles (EPA) [1], 546 km (NEDC) [2]
- Electricity needed to fill: 70 kWh [3]
- Upstream electricity / mile = 0.27 kWh (EPA)
- Upstream electricity / km = 0.13 kWh (NEDC)

- Conventional 5 seat "crossover"
- Top speed 104 mph, 0-60 mph in 7.6 seconds
- On the road price of £29,450

[1] https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=40585
[2] http://www.hyundai.com/eu/en/UpcomingVehicle/Kona-Electric/index.html
[3] https://ev-database.uk/car/1126/Hyundai-Kona-Electric-64-kWh

Replacement of Petrol Station by Wind Powered EV Charging

- The average supermarket filling station dispenses 11 million litres of fuel per year (300,000 miles sold per day)

- To replace with wind turbines
  - 90% of charging is done overnight at home [1]
  - Wind turbine capacity factor is 28%, therefore 72% will come from on-site battery storage
  - Rapid charging requires 7900 kWh per day, 330 kWh per hour
  - Total energy requirement to charge stationary storage and cars is 8700 kWh [2]
  - Number of 100 kW rapid chargers or equivalent capability needed: 7

One moderate sized 1.3 MW turbine is needed per filling station

[1] https://www.goultralow.com/press-centre/releases/2333-2/
[2] https://www.tesla.com/en_GB/powerpack/design#/

Replacement of Petrol Station by Grid Powered EV Charging

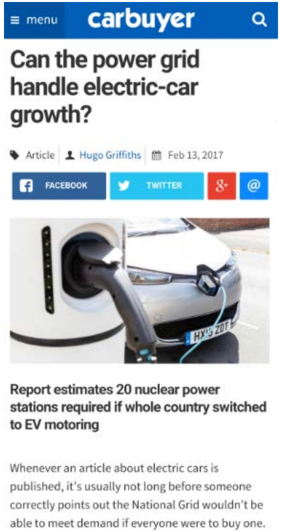
- The average supermarket filling station dispenses 11 million litres of fuel per year (300,000 miles sold per day)

- To replace with grid connected charging
  - 90% of charging is done overnight at home
  - Rapid charging requires 7900 kWh per day, 330 kWh per hour
  - So a 0.33 MW grid connection is required

- Hyundai Kona Electric (NEDC) range is 546 km

- On the 2018 UK grid this gives emissions of **32 g/km CO_2**

Can the Grid Handle 31 million EVs?



carbuyer

Can the power grid handle electric-car growth?

Article | Hugo Griffiths | Feb 13, 2017

Report estimates 20 nuclear power stations required if whole country switched to EV motoring

Whenever an article about electric cars is published, it's usually not long before someone correctly points out the National Grid wouldn't be able to meet demand if everyone were to buy one.

MailOnline

UK could need 20 more nuclear power stations if electric cars take over our roads and cause 'massive strain' on power network

- Expansion in electric cars could mean UK needs '20 more nuclear power plants'
- Research said low emission vehicles could cause 'massive strain' on power grid
- Transport for London research said London would need two power plants alone
- Comes as Department for Transport wants to boost vehicles use across Britain

679 shares

596 View comments

THE TIMES

Electric cars mean UK could need 20 new nuclear plants

Graeme Paton, Transport Correspondent

February 11 2017, 12:01am, The Times

Switching all cars to ultra-low emissions may place a massive strain on the power network

GETTY IMAGES

They are seen as an antidote to the wave of pollution clouding Britain's biggest cities. Within the next few years, it is hoped that a fleet of electric cars will clear the air by driving diesel and petrol engines off urban streets.

However, analysis has found that the burgeoning fleet of plug-in vehicles may create a new headache of its own.

Switching all cars to ultra-low emissions may place a massive strain on the power network because of the additional resources needed to recharge batteries, research suggests.

THE TIMES

Wednesday February 15 2017

Corrections and clarifications

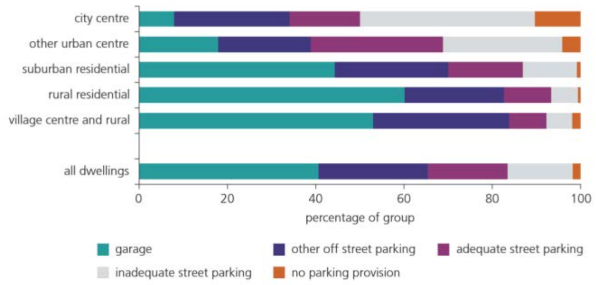
- We wrongly said (News, Feb 11) that switching all cars in Britain to battery power would require the equivalent of 20 new nuclear plants. This was a significant miscalculation based on a confusion of energy and power. We apologise for the mistake.

National Grid's FES 2018 shows that extra peak demand on the grid for all cars becoming EV is only 12.7 GW in the worst case scenario. That is the same as peak demand in 2007. Best case is 3.3 GW.[1]

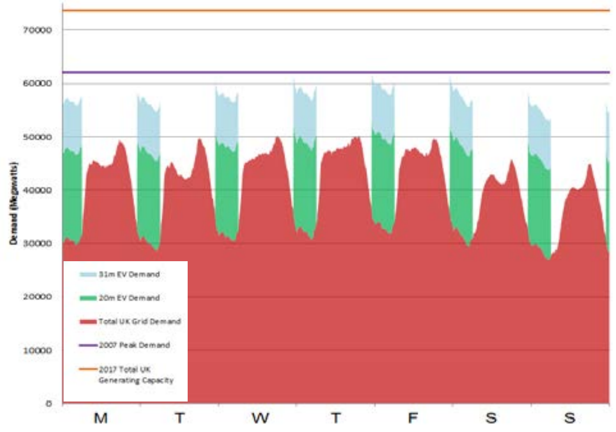
	2050 compliant						Non-2050 compliant					
	Community Renewables			Two Degrees			Steady Progression			Consumer Evolution		
	2017	2030	2050	2017	2030	2050	2017	2030	2050	2017	2030	2050
EVs numbers (Cars)	91k	10.1m	31.7m	91k	9.7m	30.7m	91k	2.6m	33.1m	91k	2.5m	33.4m
EV annual demand (Cars)	0.2 TWh	20.1 TWh	60.6 TWh	0.2 TWh	17.5 TWh	59.5 TWh	0.2 TWh	4.9 TWh	56.5 TWh	0.2 TWh	4.5 TWh	55.8 TWh
EV peak demand (inc. V2G)	0.1 GW	5.0 GW	3.3 GW	0.1 GW	8.1 GW	6.5 GW	0.1 GW	2.8 GW	12.7 GW	0.1 GW	2.6 GW	9.9 GW

[1] http://fes.nationalgrid.com/media/1373/crib-sheet-v6.pdf

Domestic EV Charging from the Grid



English Housing Survey



Power demand on National Grid over 7 days, 5th Feb 2017

- Over 80% of rural and 70% of suburban dwellings have sufficient off-street parking, enabling overnight EV charging
- Average daily mileage is 21.6 miles [1]
  - Requires 5.65 kWh from grid (based on realistic Kona EPA range)
  - 0.81 kW or 3.5 Amps during overnight Economy7 period
- UK car fleet of 30.9 million cars [1]
  - 90% charging at home overnight requires 22 GW
  - Added to existing base demand leads to a mid-winter overnight peak of 62GW (equivalent to daytime peak demand in 2007)
  - Smart grid allows smoothing of peaks to much less than 60 GW
- Total UK generation and import capacity is 78 GW [2]
  - 100% EV fleet is possible for National Grid
  - 3.5 Amps is a manageable amount for a domestic supply (although many EVs have a minimum input of 6 Amps)

The National Grid can manage significant growth in EVs, however charge time management is needed to ensure consistent demand

[1] http://www.racfoundation.org/motoring-faqs/mobility
[2] http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=8589937050

Domestic EV Charging from Solar

4.6 kW solar PV array on garage

Lithium ion, zinc-bromine salt-based flow battery or 12V lead-acid

Storage battery charged in daytime to provide power at night

Electric Vehicle

- A typical domestic or garage roof can accommodate a 4.6 kWp solar PV system (e.g. using 14 high efficiency Panasonic HIT panels) [1]
  - Combined with battery storage, an all-DC path to the car can be designed, increasing efficiency further by eliminating mains AC inverter and charger losses
- Average daily mileage is 21.6 miles
  - Requires 5.65 kWh to the car
  - Requires 6.42 kWh to be generated for battery storage [2]
- Average daily production (Derby) exceeds demand in all months [3]
  - 14 kWh storage battery can smooth variations in generation
- Total price amortises to approximately £500 per annum without subsidy

Domestic solar has the potential to offload the vast majority of EV energy demand from the grid, offering true near zero emissions driving

[1] http://panasonic.net/ecosolutions/solar/hit/#section02
[2] https://www.tesla.com/en_GB/powerpack/design#/
[3] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#

Comparison of Hydrogen Derived from Water Electrolysis and Steam Methane Reformation

H2 from Electrolysis vs. EV vs. ICE






	Hyundai Kona Electric	**Toyota Mirai**	**Renault Zoe ZE40**	**Riversimple Rasa**	**Toyota Prius**	**Range Rover Velar 2.0 TD4**
NEDC Range (km)	546*	550*	400*	354	1426*	1000*
Fuel Type	Electric	Hydrogen	Electric	Hydrogen	Petrol	Diesel
Electricity to fill (kWh)	70	**349**	**46**	93	-	-
Upstream Efficiency (Wh/km)	128	**635**	**115**	261	-	-
(UK grid) CO_2 emissions (g/km)	32	**160**	**29**	66	70*	142*
Curb weight (kg)	1685	**1850**	1480	**580**	1400	1804
Number of seats	5	4	5	**2**	5	5
Motorway speed capable?	Yes	Yes	Yes	**No**	Yes	Yes

* Manufacturer data

So what about hydrogen from natural gas?

- Steam reforming of natural methane gas produces 10.62 kg of CO_2 per 1 kg of hydrogen [1]
  - 5.5 kg directly from the chemical reaction and the rest from heat generation and other processes
- Hydrogen production accounts for 17% of total CO_2 from the European refinery sector *today* [2]
- To produce 5 kg hydrogen for the Toyota Mirai, 53.1 kg CO_2 is released
  - This gives 97 g / km CO_2 emissions from the production of the hydrogen
- However, over 10.2 kWh of electricity is needed per kg to store and pump into car
  - Adding a further 23 g / km grid CO_2 emissions
- Steam methane reformation typically happens off-site in large refinery plants
  - The hydrogen must be piped or trucked to the filling station, creating further inefficiency and emissions
  - A 500 bar hydrogen tanker carries approximately 700 kg payload, enough for 140 cars like the Mirai[3]
  - A petrol tanker carries 18x the equivalent fuel in terms of miles driven when used to fill a Toyota Prius[4]

Using natural methane gas results in at least 120 g / km CO_2 with the Mirai, 4 times the emissions from the Hyundai Kona or Renault Zoe and over 70% more than Toyota's conventional petrol-powered Prius.

[1] https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/27637.pdf
[2] http://www.itm-power.com/news-item/100mw-electrolyser-plant-designs-to-be-launched-at-hannover
[3] http://www.hysolutions-hamburg.de/fileadmin/user_upload/04_Service/Downloaddokumente/2013-10-16_IFCB-Workshop/08._Arxer_Hydrogen_Energy_Systems_FCB_WS2013.pdf
[4] http://tankquip.co.uk/products/fuels-energy/semi-trailer_fe/

H2 from Natural Gas vs. EV vs. ICE



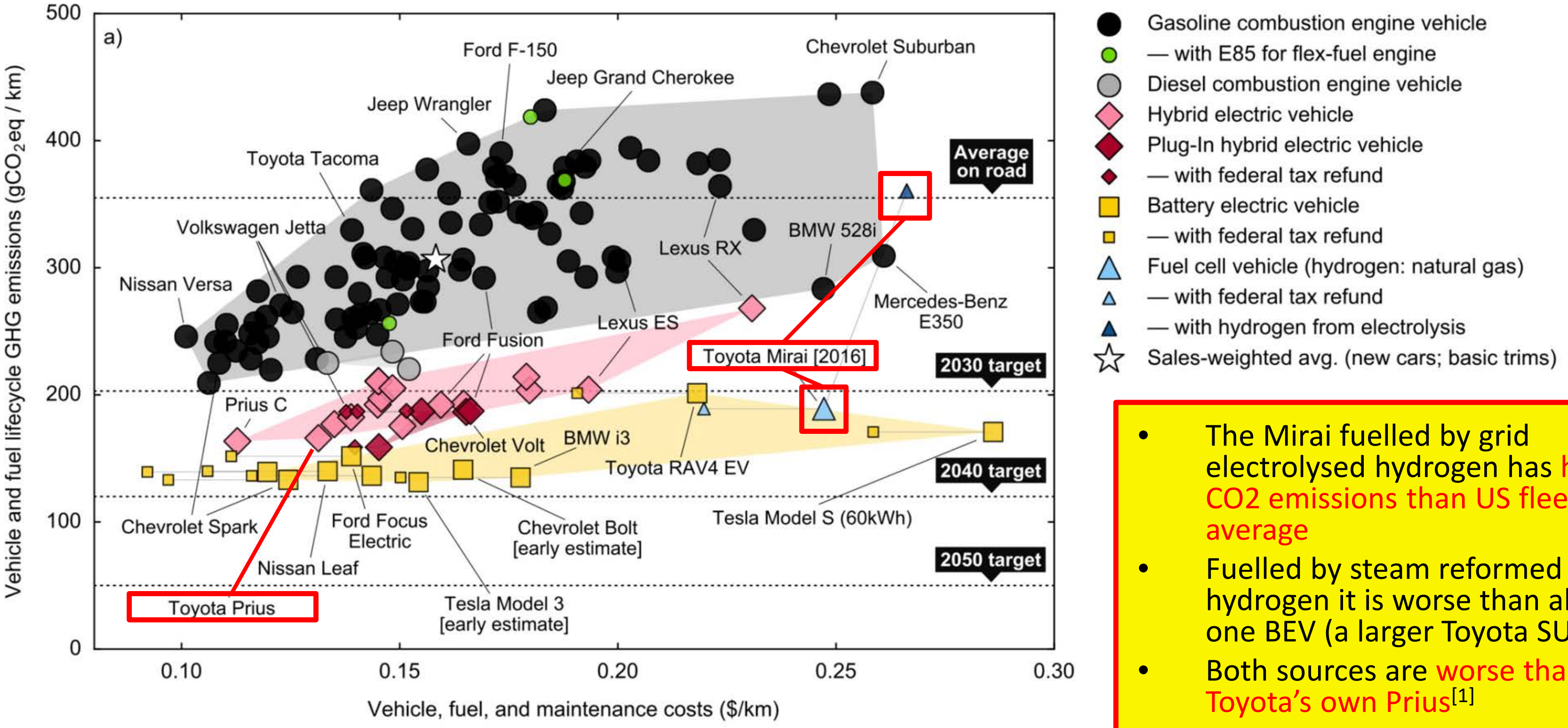



	Hyundai Kona Electric	Toyota Mirai	Renault Zoe ZE40	Riversimple Rasa	Toyota Prius	Range Rover Velar 2.0 TD4
NEDC Range (km)	546*	550*	400*	354	1426*	1000*
Fuel Type	Electric	Hydrogen	Electric	Hydrogen	Petrol	Diesel
Electricity to fill (kWh)	70	-	**46**	-	-	-
Upstream Efficiency (Wh/km)	128	-	**115**	-	-	-
(UK grid) CO2 emissions (g/km)	32	> 120	**29**	> 59	70*	142*
Curb weight (kg)	1685	**1850**	1480	**580**	1400	1804
Number of seats	5	4	5	**2**	5	5
Motorway speed capable?	Yes	Yes	Yes	**No**	Yes	Yes

* Manufacturer data

Manufacturing and Lifecycle Energy and Emissions

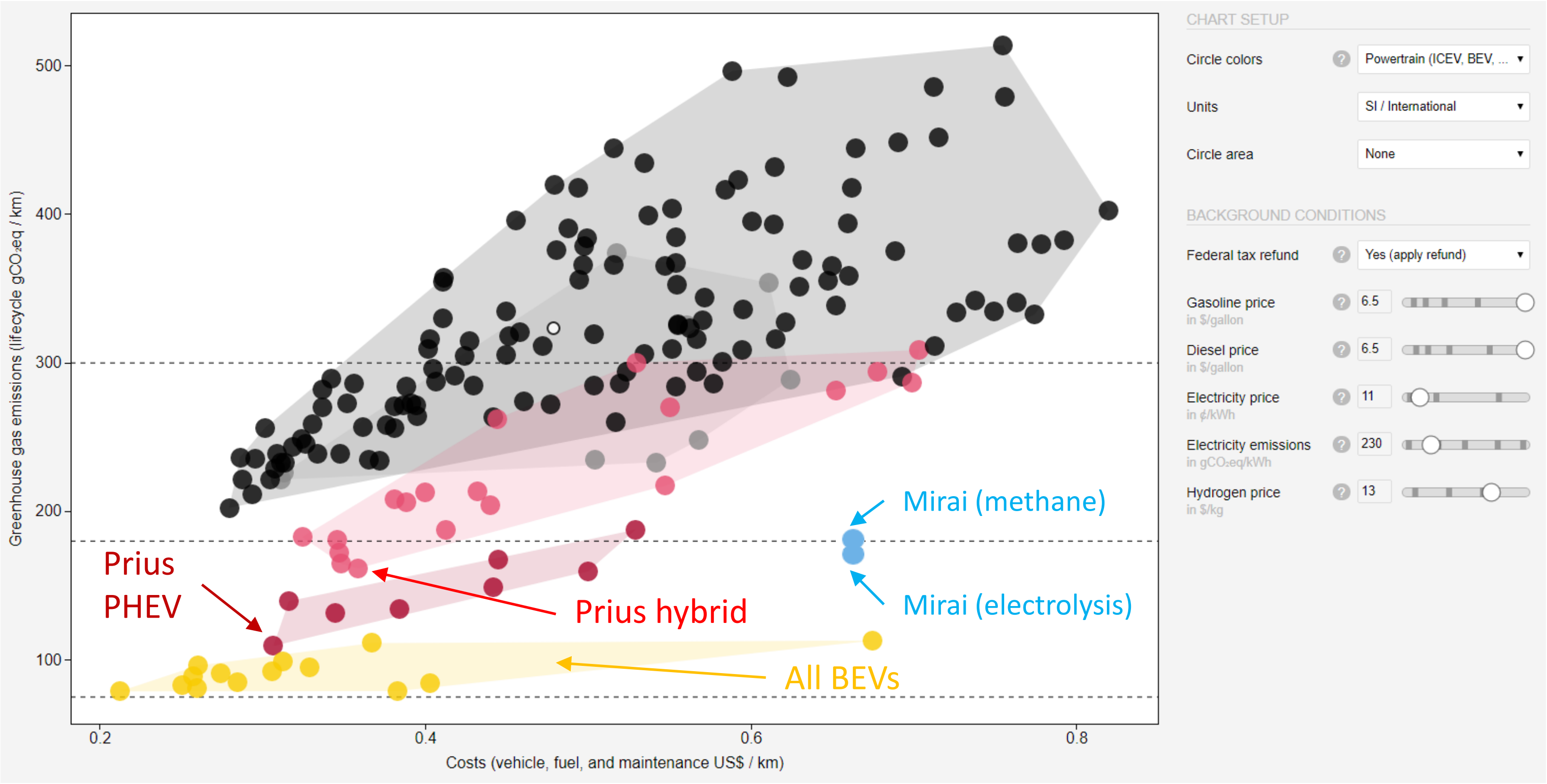
Vehicle Whole Life Cycle Emissions – US Grid



- The Mirai fuelled by grid electrolysed hydrogen has higher CO2 emissions than US fleet average
- Fuelled by steam reformed hydrogen it is worse than all bar one BEV (a larger Toyota SUV)
- Both sources are worse than Toyota's own Prius[1]

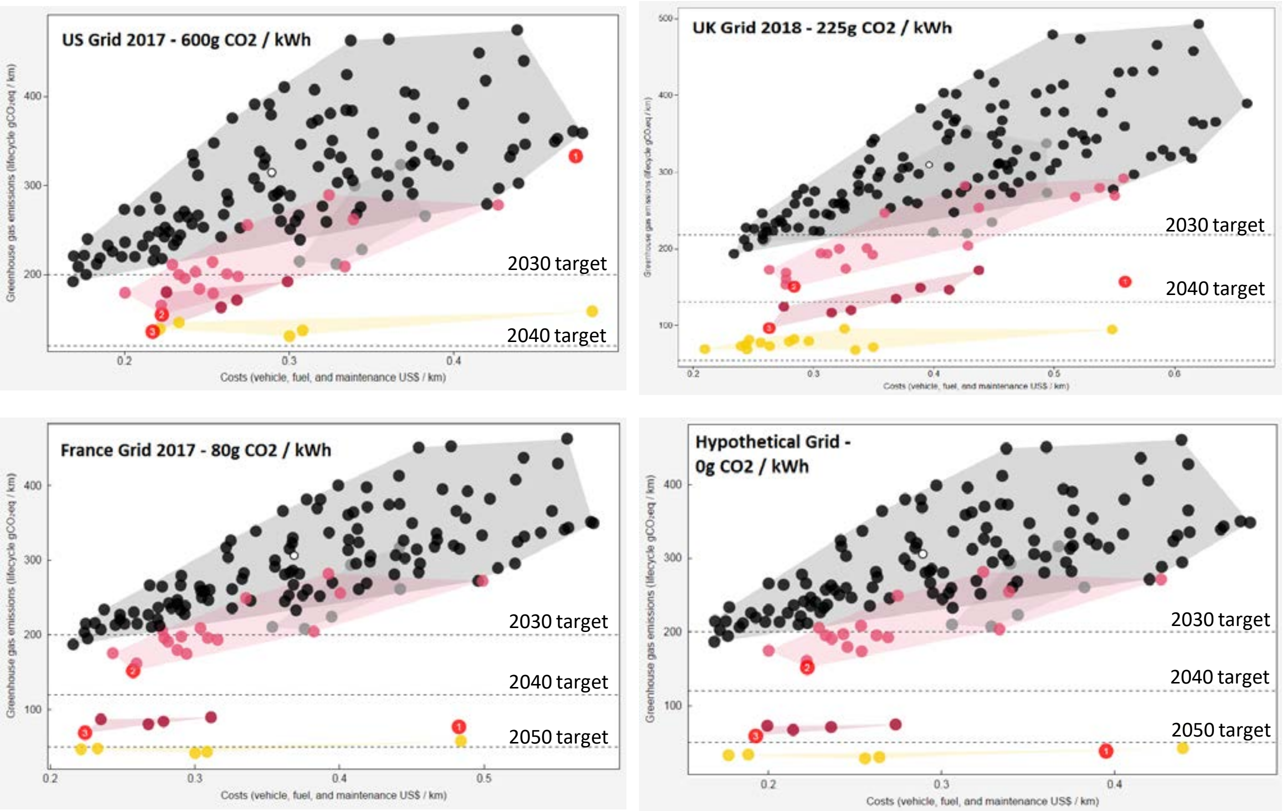
[1] *Personal Vehicles Evaluated against Climate Change Mitigation Targets, Trancik et al, MIT,* http://pubs.acs.org/doi/full/10.1021/acs.est.6b00177

Vehicle Whole Life Cycle Emissions – UK Market



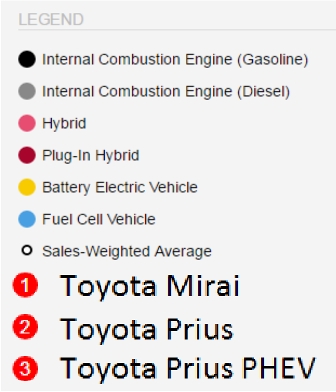
Trancik Lab, MIT, http://carboncounter.com/

Vehicle Whole Life Cycle Emissions – Grid Comparison



Each market shows local fuel prices.

No subsidies.

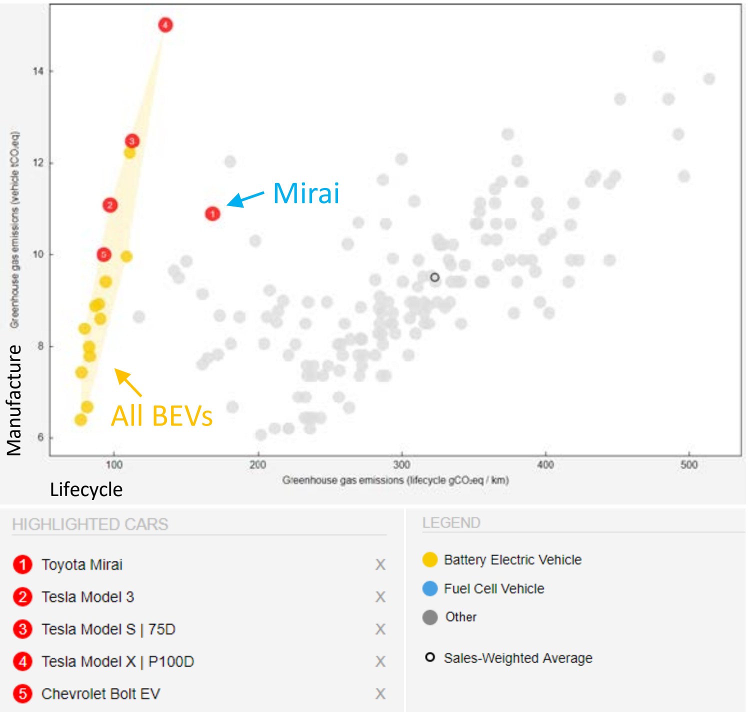


Trancik Lab, MIT, http://carboncounter.com/

Manufacturing Energy Use and Emissions

- Manufacturing energy and emissions for a hydrogen fuel cell and BEV are practically equivalent [1]
  - Energy use for production and disposal (300,000 km lifetime):
    - Hydrogen: 267 kJ/km
    - BEV: 275 kJ/km
  - CO2 emissions for production and disposal:
    - Hydrogen: 4.9 g/km
    - BEV: 5.2 g/km
- For example, Tesla Model 3 and Toyota Mirai both create 11 tonnes total CO2 emissions in manufacture, but the Model 3 has significantly lower emissions in use over its lifetime [2]

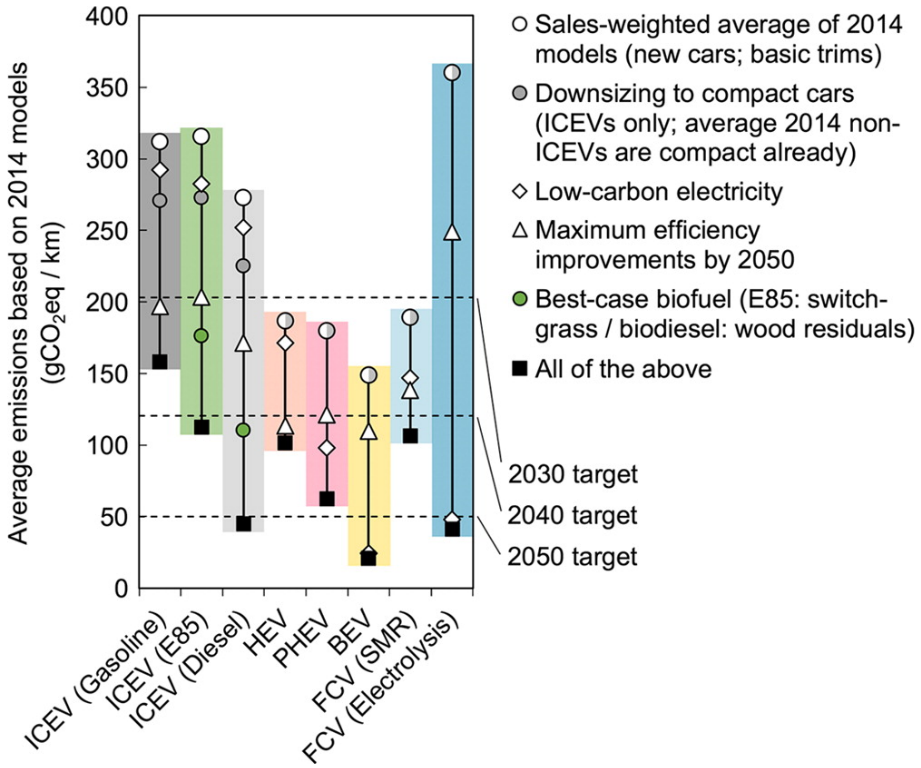
Manufacturing Emissions vs. Whole Lifetime Emissions per km [2]



8000 miles per year, 14 year lifetime, UK grid emissions

[1] *ON THE ROAD IN 2020, Weiss et al, MIT,* http://www.forschungsnetzwerk.at/downloadpub/mit_2000_el00_003_vehicle.pdf
[2] *Trancik Lab, MIT,* http://carboncounter.com/

Vehicle Whole Life Cycle Emissions – Trends



- Hydrogen vehicles today have higher lifecycle emissions than HEV and PHEVs
- Hydrogen sourced from steam reformation cannot beat HEVs and PHEVs, yet alone BEVs
- Hydrogen sourced from grid electrolysis requires significant decarbonisation to beat HEVs and PHEVs
- BEVs beat other types every time
- BEVs offer the easiest route to meet required long term climate goals[1]

[1] *Personal Vehicles Evaluated against Climate Change Mitigation Targets, Trancik et al, MIT,* http://pubs.acs.org/doi/full/10.1021/acs.est.6b00177

"There's not enough lithium for every car"

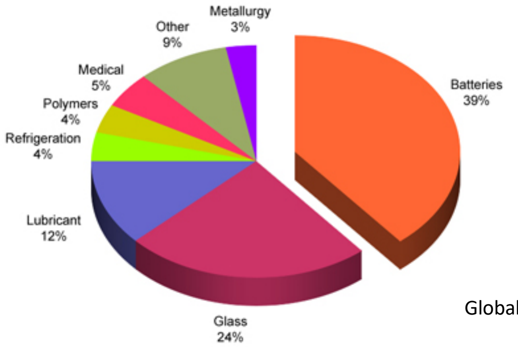
- Lithium is currently sourced from two natural resources:
  - Brine from salt flats accounts for the majority of production
  - Spodumene from rock ores
- World reserves (currently usable) are 14m tonnes [1]
- World resources (known) are 34m tonnes [1]
  - At 7kg per battery, today's reserves are sufficient to build 2 billion 70 kWh (300+ miles range) EVs
  - Identified resources would build 4.8 billion
- Lithium can be recycled at end of life
- Lithium can be substituted in batteries by sodium, nickel, zinc, magnesium

	Mine production 2014	Mine production 2015[e]	Reserves[6]
United States	W	W	38,000
Argentina	3,200	3,800	2,000,000
Australia	13,300	13,400	1,500,000
Brazil	160	160	48,000
Chile	11,500	11,700	7,500,000
China	2,300	2,200	3,200,000
Portugal	300	300	60,000
Zimbabwe	900	900	23,000
World total (rounded)	[7]31,700	[7]32,500	14,000,000

USGS 2016

Above: World lithium reserves (tonnes)

Below: Breakdown of applications for lithium



Global Lithium LLC 2016

[1] *USGS*, https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2016-lithi.pdf

Hydrogen in Heavy Vehicles

Does hydrogen have a place in heavy vehicles?

Felix O - Wikimedia

Wrightbus Pulsar Hydrogen bus

ADL

ADL / BYD Enviro 200EV electric bus

Hydrogen and BEV buses operate in London and elsewhere in the UK, however so far only electric models have been sold to operators on a commercial basis

- Wrightbus Pulsar Hydrogen Fuel Cell Bus
  - 33 kg hydrogen tanks [1]
  - 2050 kWh upstream electricity to fill (in London steam reformed hydrogen is trucked in from Rotterdam)
  - 250-300 km range [2]
  - 9 kg / 100 km efficiency [2]
  - 5.6 kWh / km
  - 1868 g / km upstream CO2 emissions if fuelled on UK grid
  - Fill time – 13 minutes at end of day [3]

- ADL / BYD Enviro 200EV eBUS
  - 324 kWh battery [4]
  - > 250 km range
  - 1.3 kWh / km
  - 434 g / km upstream CO2 emissions if fuelled on UK grid
  - Fill time – 4 hours overnight

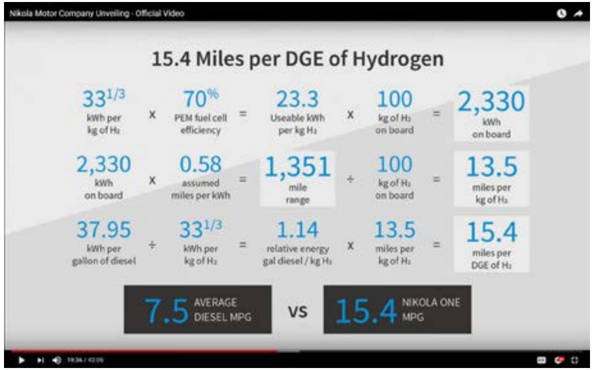
The hydrogen bus uses 4x the energy as the BEV bus while giving a similar range. Each hydrogen bus must be attended while filling, while the BEV is left overnight to charge.

[1] http://www.h2fc-fair.com/hm14/images/tech-forum-presentations/2014-04-10-1600.pdf
[2] http://ballard.com/files/PDF/Bus/TfL_Case_Study_Jan_2016.pdf
[3] http://gofuelcellbus.com/uploads/London_BusesMag_Feb_2013.pdf
[4] http://www.byd.com/la/auto/ebus.html

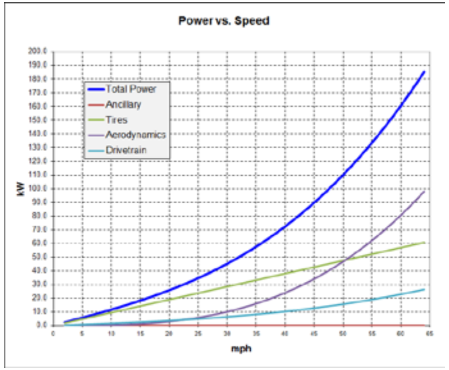
Does hydrogen have a place in heavy vehicles?

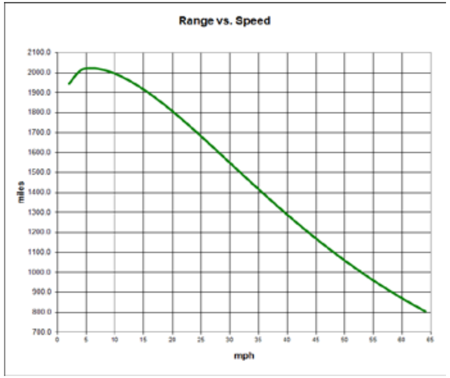
The Nikola One truck from Nikola Motor Company

- 1000 – 1200 miles claimed range [2]
- 80,000 lbs (36.3 tonnes) gross vehicle weight [2] (normal US federal maximum) [3]
- 100 kg hydrogen tank [1]
- 320 kWh buffer battery (not capable of plug-in) [1]
- Fuel cell claimed to be 70% efficient (hydrogen LHV) [1] – this claim is 17% better than any other PEM fuel cell
- Assumed Cd = 0.6 (typical range for HGV is 0.6-0.8, trailer is 60% of drag), A = 11m^2, Crr = 0.006, claimed motor and inverter efficiency 95%



Top: Slide from Nikola One launch event showing claimed efficiency [1]. Bottom Nikola One Tractor Unit.





Calculated range and power curves based on Nikola Motors data and CdA assumption

[1] https://www.youtube.com/watch?v=wLidTCqAAtY
[2] https://nikolamotor.com/press
[3] https://ops.fhwa.dot.gov/Freight/sw/overview/index.htm

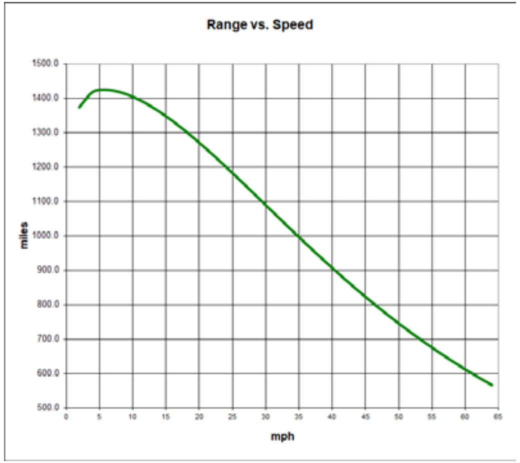
Does hydrogen have a place in heavy vehicles?

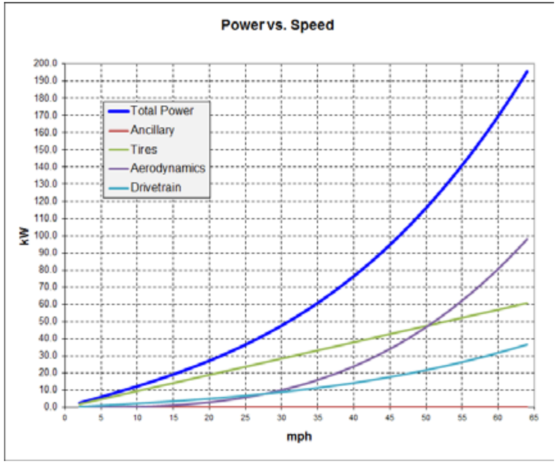
- Fuel cell really likely to be 52% efficient (using Powercell S3 fuel cell [1,2]), drivetrain 90% efficient with reduction gearing
- Hydrogen tank mass = ~2 tonnes
- Battery mass = ~2 tonnes
- Fuel cell mass = ~1 tonne
- 625 miles calculated range at 60 mph

(Hydrogen tank, battery and fuel cell mass) makes for very heavy tractor unit

- Up to 70 trucks can be filled per day from Nikola Motor Company's proposed 100 MWp solar farms [1] (based on Southern Spain data)

With 52%$_{LHV}$ efficient fuel cell,
The truck has a calculated range
of 612 miles on 100 kg hydrogen
at 60 mph, 1000 miles at 35 mph.
Efficiency in MPG equivalent
is inline with diesel.



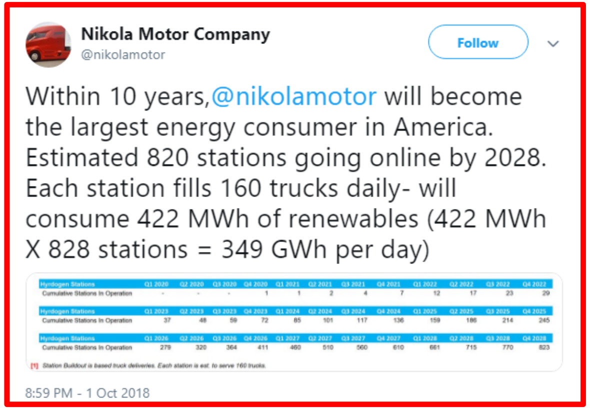


[1] https://twitter.com/nikolamotor/status/1046968808194416642
[2] http://www.ht.energy.lth.se/fileadmin/ht/Kurser/MVKF25/PowerCell_presentation_170510_LTH.pdf
[3] https://nikolamotor.com/press

Does hydrogen have a place in heavy vehicles?

- Nikola Motor tweeted [1] that they will become the largest energy consumer in America
  - Each station uses 422 MWh per day and fills 160 trucks per day
  - This means each truck uses on average 2638 kWh of upstream electricity
  - Taking the average efficiency of a filling station (69.8 kWh/kg), this makes 38 kg of hydrogen
  - The company states 2638 kWh of "renewables" needed per fill, but previously said each truck carries 100 kg of hydrogen giving 2330 kWh – this would require impossible levels of efficiency of the electrolyser, hydrogen storage, distribution and truck's fuel cell totalling 88% combined
- 349 GWh per day means an constant supply of 14.54 GW is needed
  - Average capacity factor for wind in US is 36.7%, so this requires 40 GWp of wind turbines
  - Current installed wind capacity in the US is 90 GWp, thus almost half of current output needed to supply 820 sites [2]
  - Alternatively requires 135 GWp of solar PV – 2 billion m^2 (2000 km^2) of solar panels in SoCal
  - Fills 131,200 trucks per day. There are 2 million articulated (tractor-trailer) trucks in the US [3]
- Tesla Semi has a claimed range of 500 miles using under 2 kWh/mile
  - Battery is therefore under 1000 kWh, approximate 4x more efficient than hydrogen for the same range

[1] https://twitter.com/nikolamotor/status/1046852215565049857
[2] https://www.awea.org/wind-101/basics-of-wind-energy/wind-facts-at-a-glance
[3] https://www.truckinfo.net/trucking/stats.htm
[4] https://www.tesla.com/en_GB/semi



Nikola Motor Company
@nikolamotor
Follow

Within 10 years,@nikolamotor will become the largest energy consumer in America. Estimated 820 stations going online by 2028. Each station fills 160 trucks daily- will consume 422 MWh of renewables (422 MWh X 828 stations = 349 GWh per day)

Hyrdogen Stations	Q1 2020	Q2 2020	Q3 2020	Q4 2020	Q1 2021	Q2 2021	Q3 2021	Q4 2021	Q1 2022	Q2 2022	Q3 2022	Q4 2022
Cumulative Stations In Operation	-	-	-	1	1	2	4	7	12	17	23	29

Hyrdogen Stations	Q1 2023	Q2 2023	Q3 2023	Q4 2023	Q1 2024	Q2 2024	Q3 2024	Q4 2024	Q1 2025	Q2 2025	Q3 2025	Q4 2025
Cumulative Stations In Operation	37	48	59	72	85	101	117	136	159	186	214	245

Hyrdogen Stations	Q1 2026	Q2 2026	Q3 2026	Q4 2026	Q1 2027	Q2 2027	Q3 2027	Q4 2027	Q1 2028	Q2 2028	Q3 2028	Q4 2028
Cumulative Stations In Operation	279	320	364	411	460	510	560	610	661	715	770	823

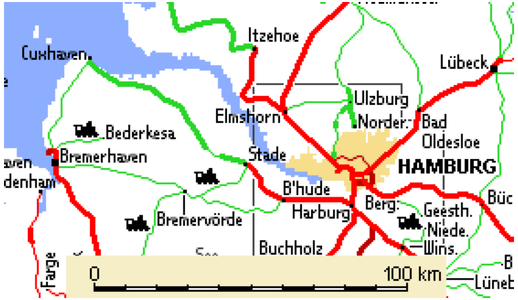
[1] *Station Buildout is based truck deliveries. Each station is est. to serve 160 trucks.*

8:59 PM - 1 Oct 2018

Top: Tweet from Nikola Motor outlining their proposed rollout of hydrogen filling stations and energy use [1]
Bottom: Tesla Semi (Wikimedia, Korbitr)

Does hydrogen have a place in heavy vehicles?

Railway Gazette



Bueker.net

Hamburg to Cuxhaven Route showing electrified (red) and non-electrified (green) sections

- Alstom Coradia iLint hydrogen powered passenger train
  - 700 km range, 188 kg hydrogen fuel, 11694 kWh electricity needed to fill [1]
  - 45% HHV efficiency of fuel cell, 2800 kWh net electricity output stored [2]
    - Ratio of energy in to energy out is 4:1
  - Approximately 1 tonne of fuel cells, 5 tonnes of tanks, 188 kg hydrogen
  - 150 seats, 0.11 kWh / seat-km
  - CO_2 emissions on UK grid: 32 g / seat-km
    - Emissions from similar size UK Class 165 diesel: 21 g / seat-km
- Capacity of train with equivalent mass of lithium-titanate batteries: 869 kWh [3] – would give a theoretical range of 216 km
- Length of unelectrified line served on test route to Cuxhaven: 61 km
  - Therefore 122 km range for return trip and 290 kW charge rate needed under wires

This train is designed to run on unelectrified track in Germany, but there are no sections of unelectrified track too long to be served by a BEV equivalent in the country…

- In Septemer 2018 Siemens announced the 244 seat Desiro Cityjet ML Eco with a 528 kWh lithium-titanate battery [4] – giving approximately 140 km battery range plus the capability to charge from overhead wires while on the move

[1] http://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/hydrogen-fuel-cell-train-order-expected-this-year.html
[2] http://www.hydrogenics.com/hydrogen-products-solutions/fuel-cell-power-systems/mobility-power/medium-duty/
[3] https://www.scib.jp/en/
[4] https://www.siemens.com/press/pool/de/feature/2018/mobility/2018-09-oebb/db-desiro-ml-oebb-cityjet-eco-e.pdf

Solution to Climate Change or Corporate Greenwash?

Are hydrogen advocates fooling us or themselves?

"The route between ITM Power's latest hydrogen refueling stations shows how commercial fleets can operate within and around central London without compromise. This enables London and further cities to meet their business, climate and air quality emissions and presents a solution for improving air quality in direct competition to the incumbent diesel powered vehicles" – *Arcola Energy, upon opening a filling station that generates on average less than 1 car's worth of zero emissions fuel per day*

"CEME is very proud to be able to offer a site for this hydrogen fuel station and utilise our solar energy to make a fuel for vehicles. It is perfectly located to offer a clean hydrogen source for London and improve air quality for London" – *CEME, again upon opening a filling station that generates on average less than 1 car's worth of zero emissions fuel per day*

"It is another example of Shell's commitment to providing low carbon fuels for the future and we hope will provide further encouragement to other stakeholders to support and invest in hydrogen. Shell's experience from partnerships in Germany and the US shows vehicle manufacturers, fuel suppliers and governments need to work together for hydrogen mobility to succeed" – *Shell, the 5th largest company in the world in 2016 by revenue, on announcing their first UK hydrogen station supported by UK and EU public funding*

"And when these advances are made, hydrogen can fill critical energy needs beyond transportation. Hydrogen can also be used to heat and generate electricity for our homes. The future possibilities of this energy source are enormous." – *Dan Lipinski, US politician. Unfortunately, as we have seen, hydrogen is not an energy source but an energy carrier that wastes the majority of energy put into it*

"If you're going to pick an energy storage mechanism, hydrogen is an incredibly dumb one to pick" – *Elon Musk, CEO SpaceX and Tesla*

"The well to wheel relationship from the energy source to the vehicle is a disaster … [hydrogen] makes some sense if you just want to get rid of energy" – *Wolfgang Ziebart, technical design director, Jaguar Land Rover*

Hydrogen Costs to the End User

- In 2012 hydrogen cost was projected to be £6.23 / kg (when using a 10 year amortisation period for equipment) [1]. By 2013 this was claimed to be down to £4.19 / kg, with £2.47 / kg achievable in the long term after amortisation [2]
  - The 2012 EU target was £7.92 / kg by 2015, falling to £4.40 / kg in 2025 if hydrogen is produced at large scale [1]
- In 2016 and 17 multiple wholesale contracts were announced at £10 / kg [3] – "*the lowest priced hydrogen in the UK*" [4]
- Wholesale electricity, water and 10 year amortisation cost give ~£5 / kg floor
  - UK wholesale cost of electricity is forecast to nearly double by 2025, leading to ~£7 / kg before tax [5]
- Long term, the retail price will include site overheads, staff and tax
  - These elements today make up approximately three quarters of retail petrol price today [6]

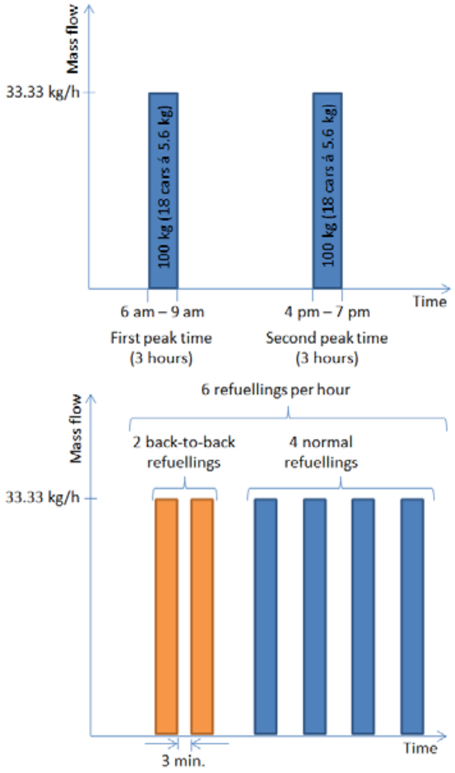
Hydrogen price at a UK filling station

Telegraph

[1] http://www.itm-power.com/news-item/update-on-hydrogen-cost-structure
[2] http://www.itm-power.com/news-item/hydrogen-cost-structure-update
[3] http://www.itm-power.com/news-media/news
[4] http://www.itm-power.com/news-item/itm-power-signs-fuel-contract-with-arcola-energy
[5] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65722/7019-annex-f-price-growth-assumptions.xls
[6] http://visual.ons.gov.uk/fuel-prices-explained-a-breakdown-of-the-cost-of-petrol-and-diesel/

Hydrogen Fill Times – the 3 Minute Myth

- Hydrogen advocates like to promote the idea of a 3 minute fill-up, just like using a petrol or diesel pump
- However drivers on the ground report times of 10 minutes or more:
  - "Berkman notes, however, that the heavily promoted 'three-minute refuelling' generally takes closer to 10 minutes. He's never once completed a fill-up in less than three minutes" [1]
  - "If you have an FCV, you can refill in and be back on the road on ten minutes" [2]
  - "Average refuelling times are now back to around ten minutes if you don't have to wait" [3]
- A hydrogen refill must be supervised – an EV does not
  - 10 minutes in the cold and rain vs. getting a coffee or food while charging…
- A known problem is waiting a while for the station to re-pressurise and cool down immediately following a fill by another driver
- The EU's PHAEDRUS project seeks to develop a €1,000,000 capital expenditure to install, 200 kg per day filling station with capability to fill 6 cars per hour and back-to-back wait times of 3 minutes before refilling [4]
  - This capability is yet to be demonstrated in practice



PHAEDRUS projected refuelling patterns [4]

[1] https://www.greencarreports.com/news/1098233_hyundai-tucson-fuel-cell-early-drivers-discuss-experiences-traveling-on-hydrogen
[2] Toyota advertorial https://www.roadandtrack.com/new-cars/car-technology/a31787/life-with-hydrogen-fuel-car-mirai/
[3] Aftermath of hydrogen shortage https://tiremeetsroad.com/2018/08/03/socal-hydrogen-refueling-stations-back-to-normal-following-shortage-fiasco/
[4] http://www.phaedrus-project.eu/userdata/file/Presentations/PHAEDRUS%20presentation%20at%20WES%20151012%20by%20HyET%20Peter%20Bouwman.pdf

Ultra-Rapid EV Charging

- The EV charging networks are now rolling out 400 kW charging stations
  - CHAdeMO association has released CHAdeMO 2.0 spec for 400 kW [1]
  - CharIN e. V. has released CCS 2.0 spec for 350 kW [2]
  - Tesla is expect roll out their similar “Supercharger 3.0” shortly
- The chargers can deliver up to 66 kWh in 10 minutes
  - This is sufficient for approximately 250 miles or 400 km in BEVs equipped with an 800 Volt battery
- Chargers are being installed now by Ionity [4], BP [4], Chargepoint [4] and Electrify America [4]
- Ionity charges 8 CHF (6 GBP) per session - this is up to 8x cheaper than an equivalent refill of hydrogen by distance
- National Grid has announced it is planning to equip UK Motorway Service Areas with 350 kW charging hubs [5]
  - Work is ongoing with MSA operators to upgrade grid connections for sufficient capacity

Clockwise from below: Ionity 350 kW chargers in Switzerland [3]. Ionity pricing screen (8 CHF per session, 6 GBP approx). 400 kW liquid-cooled lightweight cable on Ionity charging station in Switzerland. Electrify America 350 kW dual-standard charger [3]. Chargepoint Express+ 500 kW dual-standard charger [4].

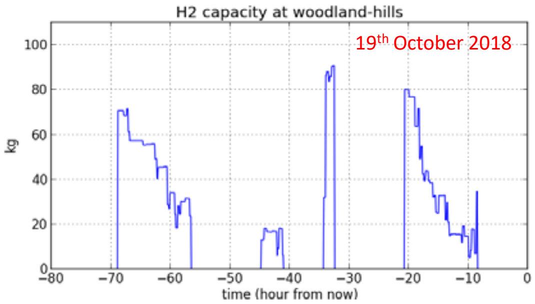
[1] https://www.chademo.com/chademo-releases-the-latest-version-of-the-protocol-enabling-up-to-400kw/
[2] https://www.charinev.org
[3] https://new.abb.com/ev-charging/
[4] https://www.chargepoint.com/products/commercial/express-plus/
[5] https://www.nationalgrid.com/sites/default/files/documents/Electric%20Vehicle%20Charging%20-%20enabling%20the%20switch.pdf

California Hydrogen Supply Problems

- In July 2018 and September 2018 multiple Air Products hydrogen production plants in Southern California went offline[1,2]
  - The company cited “multiple unrelated issues at several liquid hydrogen production and supply sites”[3]

- Many hydrogen filling stations in the area ran out of fuel for up to 3 weeks, leaving drivers with no option but to use alternative means of transport

Hydrogen advocates like to suggest the grid cannot supply large numbers of EVs, but the reality is in a key target market the established commercial hydrogen industry can not reliably supply a few hundred cars



Top: Picture posted on Twitter showing notice stuck to pump during the July 2018 SoCal hydrogen shortage. Bottom: Graph showing reserves at a SoCal hydrogen station frequently reaching zero. This is not uncommon. [4]

[1] https://tiremeetsroad.com/2018/07/24/hydrogen-fuel-shortage-in-southern-calfiornia/
[2] https://tiremeetsroad.com/2018/09/15/mayhem-in-socal-for-fcv-owners-as-shortage-hits-air-products-gives-update-through-toyota/
[3] https://tiremeetsroad.com/2018/07/28/air-products-admits-to-hydrogen-supply-chain-disruption-in-socal/
[4] http://h2-ca.com/

The Hydrogen Council

Air Liquide creative oxygen | ALSTOM | AngloAmerican | BMW GROUP

DAIMLER | engie | HONDA | HYUNDAI

Kawasaki | THE LINDE GROUP | TOTAL | TOYOTA

- Launched in January 2017 at the World Economic Forum in Davos [1]
- Made up of the CEOs of 13 automakers, oil companies and hydrogen suppliers
- Over $1 trillion in collective annual revenues
- Calling for government support and policy to invest over $20bn per year [2]

[1] http://newsroom.toyota.co.jp/en/detail/mail/14752165
[2] http://hydrogencouncil.com/hydrogen-scaling-up-new-roadmap-launches-at-cop-23/

Hydrogen Subsidies

- European Union's Fuel Cells and Hydrogen Joint Undertaking:
  - €467 million in period 2008-13 [1]
  - €665 million in period 2014-20 [2,3]

- USA spent $1.7 billion on the Hydrogen Fuel Initiative, in addition to the complementary FreedomCAR initiative, between 2003 and 2008 [4,5]

> *"President Bush is merely playing a shell game with these funds," says Patricia Monahan, a senior transportation analyst at the Union of Concerned Scientists. "The increases in the budget for hydrogen-related projects were very nearly matched by the decreases in the budget for energy efficiency and renewables."* [6]

[1] http://hydrail.org/sites/hydrail.org/files/6_navas.pdf
[2] http://www.fch.europa.eu/page/who-we-are
[3] https://setis.ec.europa.eu/system/files/Setis_magazine_10_2015_v14_WEB.pdf
[4] https://georgewbush-whitehouse.archives.gov/ceq/hydrogen_090908.html
[5] https://georgewbush-whitehouse.archives.gov/news/releases/2003/02/20030206-2.html
[6] http://grist.org/article/tough/

The right use of public resources?

Funded by UK Government

The hydrogen industry promotes the idea of zero emissions hydrogen produced directly at filling stations using off-grid renewable resources

This brushes over the fact that the process of producing such hydrogen is hugely inefficient – a windmill connected directly to a hydrogen pump filling a hydrogen car looks impressive to the politicians and journalists

However the numbers are clear: At worst such promotion is misleading and at best it is deluded

The reality is such filling stations can only service a few cars and must be grid connected to scale to replace today's commercial petrol stations, thus FCVs emit 3 to 5 times the CO_2 per km as a BEV

Where hydrogen is reformed from natural gas, CO_2 emissions are still 4x the level of a BEV charged from the UK grid, higher than emissions from a Toyota Prius and, unlike a BEV, will not get significantly better as the grid is further decarbonised. It ties transport into ongoing reliance on a fossil fuel

The right use of public resources?

The capital cost of such filling stations is significantly higher than equivalent BEV rapid charging infrastructure. This cost is being met in part with public funds – in some cases subsidising Shell, the 5th largest company in the world, to provide fuel to cars built by Toyota, the 8th largest

Hydrogen vehicles are significantly less efficient than BEVs, emit higher upstream emissions, are still expensive to produce after billions invested by governments worldwide, require an extremely expensive new fuelling infrastructure to be built from scratch, cannot easily be fuelled at home and tie drivers to the £50 fill up

It is clear that for every penny spent on supporting hydrogen, significantly more benefit can be derived from supporting BEV adoption in terms of emissions reduction and rollout of infrastructure. One hydrogen electrolyser and pump costs 60+ times that of an EV rapid charger with equivalent daily throughput [1, 2]

The cost of such a hydrogen filling station is less than 1 hour’s net profit for Shell [3]

Equivalent funding would enable a site with more than 60 bays of 120 kW EV rapid chargers

[1] A 100kg/day station has typical cost of US $1.6M. A 5000 kg/day supermarket-sized station modelled cost is US $17M: https://www.nrel.gov/docs/fy13osti/56412.pdf

[2] Tesla Supercharger cost now $25k per bay - $250k for a 10 bay site http://www.crains.com/article/news/arlingtons-pursuit-tesla-pays-urban-supercharger

[3] Shell Q3 2017 net profit was $4.1bn https://www.cnbc.com/2017/11/02/shell-earnings-q3-2017.html

In Summary

- The theory behind the 2006 IEEE paper “Does a Hydrogen Economy Make Sense?” is fully borne out in practice by real world data
- The concept of a fully off-grid renewables-powered hydrogen filling station is unworkable in the real world – the volumes of hydrogen made are pitiful. It is pure greenwash, a smokescreen to enabled the deployment of ‘brown’ hydrogen derived from fossil fuels and allow incumbents to retain control of the supply chain
- There is no hydrogen vehicle that can compete with upstream grid CO2 emissions of a BEV – this applies to cars, buses and trains. Renewable energy is more effective when sold to the grid in reducing overall emissions
- An investment of billions is needed to build out hydrogen infrastructure. Millions in public funding has already been put into sites that can sustainably fill at best a handful of cars per day
- The advocates for hydrogen are often some of the world’s biggest companies, yet they are unwilling to self-fund this infrastructure build
- Every Pound, Dollar, Euro or Yen put into funding hydrogen could have been orders of magnitude more effective at reducing oil dependence and greenhouse gases by funding electric vehicle development, infrastructure deployment and grid-scale battery storage

Hydrogen station, Heathrow
Blocked to the general public

Tesla Model S – 395 miles, refuel at any socket