

Hydrogen Engines

Dr Owen Williams – University of Wales TSD:

Liquid hydrogen (LH₂ or LH₂) is the liquid state of the element hydrogen. Hydrogen is found naturally in the molecular H₂ form.

To exist as a liquid, H₂ must be cooled below hydrogen's critical point of 33 K. However, for hydrogen to be in a fully liquid state without boiling at atmospheric pressure, it needs to be cooled to 20.28 K (–252.87 °C). One common method of obtaining liquid hydrogen involves a compressor resembling a jet engine in both appearance and principle. Liquid hydrogen is typically used as a concentrated form of hydrogen storage. As in any gas, storing it as liquid takes less space than storing it as a gas at normal temperature and pressure.

The liquid density is very low compared to other common fuels. Once liquefied, it can be maintained as a liquid in pressurized and thermally insulated containers.

Water	997 g/L
Diesel	832 g/L
Gasoline	757 g/L
Liquid Hydrogen	70.85 g/L

Liquid hydrogen is a common liquid rocket fuel for rocketry applications. NASA and the United States Air Force operate a large number of liquid hydrogen tanks with an individual capacity up to 3.8 million litres. In most rocket engines fuelled by liquid hydrogen, it is burned to produce water with traces of ozone and hydrogen peroxide.

Liquid hydrogen can be used as the fuel for an internal combustion engine or fuel cell. Concept hydrogen vehicles have been built using this form of hydrogen (see DeepC, BMW H2R). Due to its similarity, manufacturers can sometimes modify and share equipment with systems designed for liquefied natural gas (LNG). However, because of the lower volumetric energy, the hydrogen volumes needed for combustion are large. Unless direct injection is used, a severe gas-displacement effect also hampers maximum breathing and increases pumping losses.

The first thermonuclear bomb, Ivy Mike, used liquid deuterium (²H₂), for nuclear fusion.

Liquid Hydrogen:

Liquid hydrogen or 'slush hydrogen' may be used, as in the Space Shuttle. However liquid hydrogen requires cryogenic storage and boils around 20.268 K (–252.882 °C). Hence, its liquefaction imposes a large energy loss (as energy is needed to cool it down to that temperature). The tanks must also be well insulated to prevent boil off but adding insulation increases cost.

Liquid hydrogen has less energy density by volume than hydrocarbon fuels such as gasoline by approximately a factor of four. This highlights the density problem for pure hydrogen: there is actually about 64% more hydrogen in a litre of gasoline (116 grams hydrogen) than there is in a litre of pure liquid hydrogen (71 grams hydrogen). The carbon in the gasoline also contributes to the energy of combustion.

HYDROGEN STORAGE:

Compressed hydrogen

Compressed hydrogen is a storage form where hydrogen gas is kept under pressures to increase the storage density. Compressed hydrogen in hydrogen tanks at 350 bar (5,000 psi) and 700 bar (10,000 psi) is used for hydrogen tank systems in vehicles, based on type IV carbon-composite technology. ^[*] Car manufacturers have been developing this solution, such as Honda and Nissan.

[*] Eberle, Ulrich; Mueller, Bernd; von Helmolt, Rittmar (2012). "Fuel cell electric vehicles and hydrogen infrastructure: status 2012". *Energy & Environmental Science*. 5 (10): 8780

Liquid hydrogen

BMW has been working on liquid hydrogen tanks for cars, producing for example the BMW Hydrogen 7.

Hydrogen is liquified by reducing its temperature to -253°C , similar to liquified natural gas (LNG) which is stored at -162°C .



BMW claims the Hydrogen 7 is the “world’s first production-ready hydrogen vehicle”; thus far, the Hydrogen 7 has only been released to select high-profile leases. There is doubt, however, over whether or not this automobile will ever be put into larger production, even if hydrogen fuel technology reaches the point of economical and “green” feasibility, as well as to have the infrastructure required to put hydrogen vehicles in demand.

The Hydrogen 7 uses more fuel than many trucks, consuming 13.9 L/100 km for gasoline (petrol) and 50 L/100 km for hydrogen

Fuel Consumption Table for the BMW Hydrogen 7

Gasoline		Hydrogen	
L/100 km	MPG	L/100 km	MPG
13.9	20.3	50	5.6

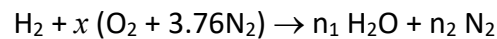
The difference in fuel consumption is largely due to the different energy density with gasoline (petrol) yielding 34.6 MJ/L and liquid hydrogen yielding 10.1 MJ/L. Based on these energy density figures, one would expect 47.6 L/100 km for hydrogen based on 13.9 L/100 km for gasoline (petrol); which is very close to the stated 50.0 L/100 km.

Combustion of Hydrogen

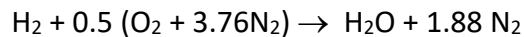
Dr Owen Williams – University of Wales TSD:

Using hydrogen in an internal combustion engine, efficiency-wise looks like a great idea since hydrogen burns the fastest, since H_2 is the fastest and lightest of all the molecules at a given temperature; therefore will have a very fast flame front during combustion.

This would enable us to have a later (more retarded) ignition point, less negative work and also less time for heat loss!



$H \rightarrow 2$	$n_1 = 1$
$O \rightarrow 2x$	$2x = 1 \text{ so } x = 0.5$
$N \rightarrow 0.5 (3.76)$	$= 1.88$



The enthalpy analysis of this reaction yields $0 \rightarrow 242MJ + 0$

So one kmol of H_2 has the net enthalpy released of 242MJ
(This is 2kg of H_2 ... So one kg will yield 121MJ)

So we know the calorific value of Hydrogen (or LHV) is = 121 MJ/kg

Compare this with gasoline at = 44MJ/kg

And also, Lithium Ion Battery Energy Density = 0.7 MJ/kg

In port injection, the mixture comes along the port, so for the same displacement the volume of the mixtures sucked in is the same.

$$\text{Ideal Gas Law} \rightarrow PV = nR_uT$$

The pressure is proportional to the temperature
The volume is proportional to the number of kmols

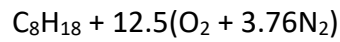
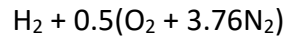
Considering the BMW Hydrogen 7, the number of kmols of mixture into the engine has to be the same for both H_2 and for gasoline.

Energy Released per kmol of mixture:

H_2	Gasoline
$\frac{242}{(1+0.5(1+3.76))} = 71.6 \text{ MJ/kmol}$	$\frac{5100}{(1+12.5(1+3.76))} = 84.3 \text{ MJ/kmol}$

From this, it can be seen that H₂ produces less energy for the same volume. You would need to turbo-charge the engine or supercharge it to get the power back!

Let us use the chemical equations to look at the volumes of fuel required.



Since $PV = nR_uT$, for the same pressure and temperature we know that:

The *volume* of O₂ is proportional to the *kmols* of O₂

The *volume* of H₂ is proportional to the *kmols* of H₂

The *volume* of **Air** is proportional to the *kmols* of **Air**

$$\frac{\text{Vol H}_2}{\text{Total Vol}} = \frac{1}{(1 + 0.5(1 + 3.76))} = 0.29$$

$$\frac{\text{Vol Gasoline}}{\text{Total Vol}} = \frac{1}{(1 + 12.5(1 + 3.76))} = 0.02$$

This means that Hydrogen takes up nearly 30% of the total volume,
whereas gasoline takes up 2%

There is therefore obviously much less oxygen going in with the H₂ hence the need to
'pressure charge' it in some way.

Hydrogen Fuel Cells

Dr Owen Williams – University of Wales TSD:

Using hydrogen in an internal combustion engine as a source of energy is far less efficient than fuel cell technologies;

The FUEL CELL

Hydrogen + Oxygen = Electricity + Water Vapor

Anode: $2\text{H}_2 \rightarrow 4\text{H}^+ + 4\text{e}^-$

Cathode: $\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$

Overall: $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$

A fuel cell is a device that converts chemical potential energy (energy stored in molecular bonds) into electrical energy.

A PEM (Proton Exchange Membrane) cell uses hydrogen gas (H_2) and oxygen gas (O_2) as fuel. The products of the reaction in the cell are water, electricity, and heat. This is a big improvement over internal combustion engines, coal burning power plants, and nuclear power plants, all of which produce harmful by-products.

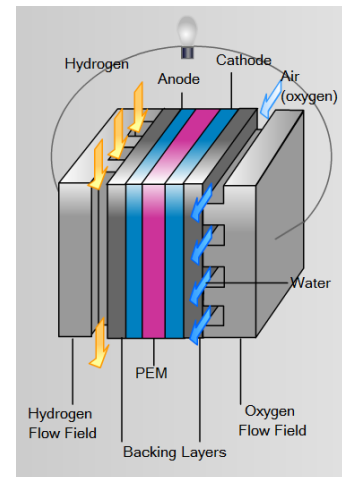
Since O_2 is readily available in the atmosphere, we only need to supply the fuel cell with H_2 which can come from an electrolysis process (see earlier issues – will be covered in more detail further on).

There are four basic elements of a PEM Fuel Cell:

The anode, the negative post of the fuel cell, has several jobs. It conducts the electrons that are freed from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.

The cathode, the positive post of the fuel cell, has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst, where they can recombine with the hydrogen ions and oxygen to form water.

The electrolyte is the proton exchange membrane. This specially treated material, which looks something like ordinary kitchen plastic wrap, only conducts positively charged ions. The membrane blocks electrons. For a PEMFC, the membrane must be hydrated in order to function and remain stable.



The catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum nanoparticles very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the PEM.



As the name implies, the heart of the cell is the proton exchange membrane. It allows protons to pass through it virtually unimpeded, while electrons are blocked. So, when the H_2 hits the catalyst and splits into protons and electrons (remember, a proton is the same as an H^+ ion) the protons go directly through to the cathode side, while the electrons are forced to travel through an external circuit. Along the way they perform useful work, like lighting a bulb or driving a motor, before combining with the protons and O_2 on the other side to produce water.

So how does it work?

Pressurized hydrogen gas (H_2) entering the fuel cell on the anode side.

This gas is forced through the catalyst by the pressure. When an H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell.

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O).

All these reactions occur in a so called 'cell stack'.

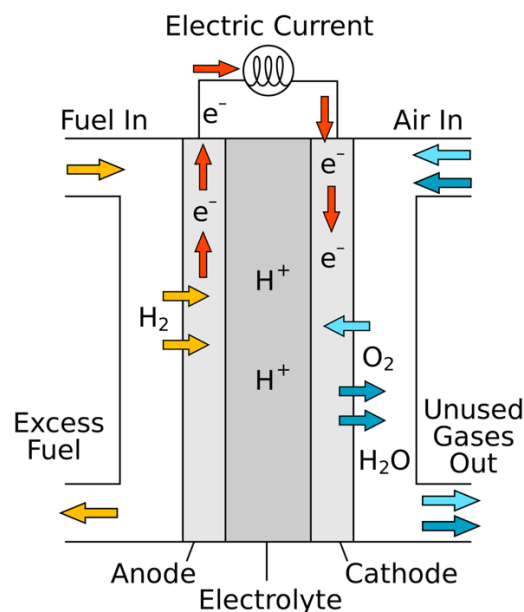
The 'trick' involves the setup of a complete system around core component that is the cell stack.

The stack will be embedded in a module including fuel, water and air management, coolant control hardware and software. This module will then be integrated in a complete system to be used in different applications.

Due to the high energetic content of hydrogen and high efficiency of fuel cells (55%), this technology can be used in many applications like transport (cars, buses, forklifts, etc), and backup power to produce electricity during a failure of the electricity grid.

Advantages of the technology:

- By converting chemical potential energy directly into electrical energy, fuel cells avoid the “thermal bottleneck” (a consequence of the 2nd law of thermodynamics) and are thus inherently more efficient than combustion engines, which must first convert chemical potential energy into heat, and then mechanical work.
- Direct emissions from a fuel cell vehicle are just water and a little heat. This is a huge improvement over the internal combustion engine’s litany of greenhouse gases.
- Fuel cells have no moving parts. They are thus much more reliable than traditional engines.



Nonetheless, hydrogen fuel (whether converted to energy in fuel cells or burned in an internal combustion engines) is not as green as it may seem; particularly so when you also consider that producing gaseous and especially liquid hydrogen requires vast amounts of energy.

Electric Vehicles

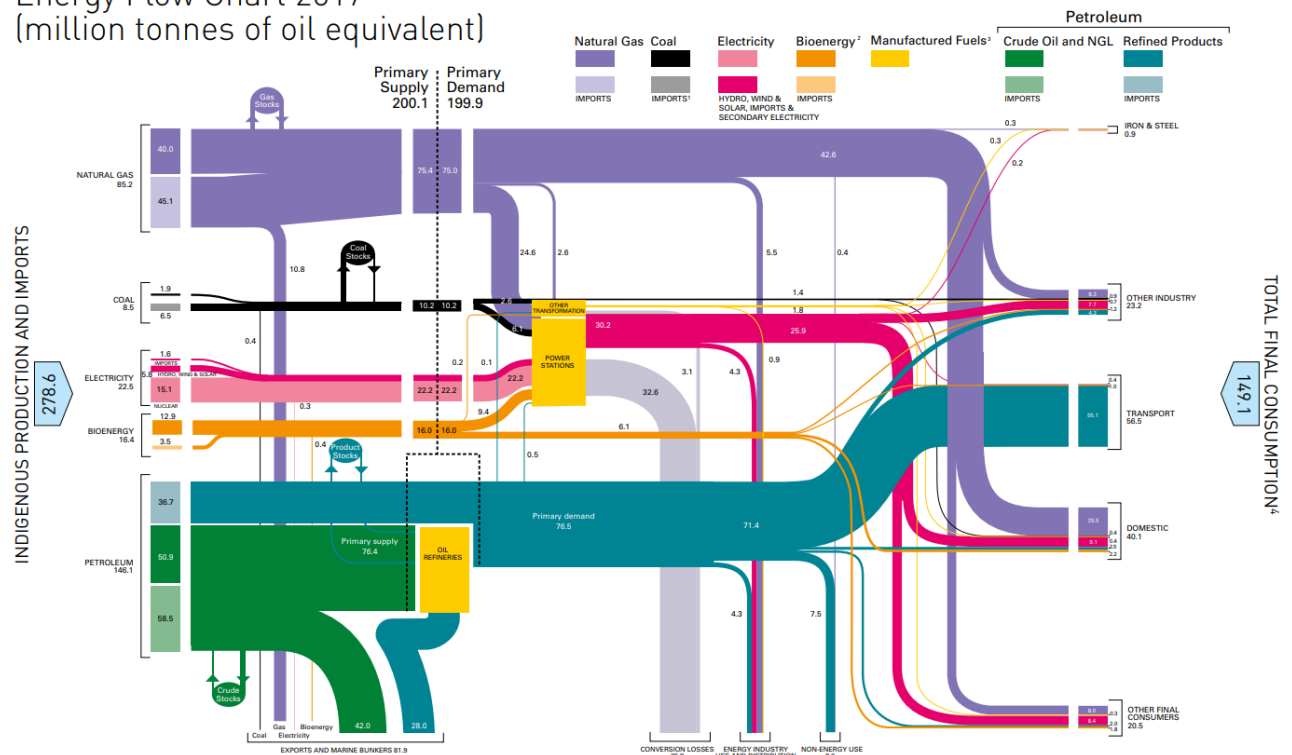
Dr Owen Williams – University of Wales TSD:

To get a better understanding of the role electric vehicles may play, let us take a look at energy more generally...

The Department for Business, Energy & Industry Strategy (BEIS) published the 2017 energy flow in July 2017. This shows that our use of coal has all but been eliminated and has been largely replaced by 'lower carbon' natural gas. The other points of note are:

1. The main consumers of energy are still the transport, domestic and industry sectors, but the order has now reversed
2. 54% of the UK's primary energy is now imported
3. The primary energy conversion and transmission losses in electricity consumer supply have only dropped from 72% to 64% in forty years
4. Most troubling of all, the move to renewable energy has resulted in only 22.2 million toe (tonne of oil equivalent) of our primary energy being displaced. That amounts to just 8% of the total primary energy production and imports.

Energy Flow Chart 2017
(million tonnes of oil equivalent)



It's clear we need to be much more ambitious in our reduction in greenhouse gas emissions than ever before. We need to reduce our consumption, drive fewer miles, take fewer foreign holidays, eat less meat and dramatically increase our renewable energy production. However, this may not be sufficient.

Currently, the biggest energy use in the UK economy is transport and moving the transport fleet to electric vehicles is likely to be inadequate. The need to increase our renewable electricity from the current 5.8 million toe to around 90 million toe is ambitious to say the least, as is the idea of tripling the capacity of the national grid.

What does the national grid have to say about it all?



"The momentum behind the shift towards electric vehicles (EVs) is now clearer than ever. The UK Government's announcement to stop all sales of petrol and diesel cars by 2040 is the latest in a string of high-profile policy decisions in recent months.

France, of course, has already announced its own ban on petrol and diesel vehicles by 2040. Car manufacturer Volvo will produce only electric or hybrid vehicles from 2019. Meanwhile, BMW has announced that an electric version of the Mini will be built in the UK, with production starting in 2019.

These are seismic decisions, when you consider that at present there are only around 100,000 electric vehicles in the UK, which compares with a total car fleet of 31 million. The full details of the government's announcement are still being studied, but the message is unavoidable – EVs are on the rise and it's now a question of 'when' not 'if' the transition from the internal combustion engine will happen."

What the 2017 FES say about EVs

"The future of EVs formed part of our analysis when we published the *2017 Future Energy Scenarios (FES)* in mid-July. Of course it's legitimate to ask whether that analysis has since been overtaken by the government announcement, but in fact high growth of EVs does fit within our scenario range.

So, what do our different scenarios say? In all scenarios except Steady State we see a dramatic rise in EVs, with sales being more than 90% of all cars by 2050. Two Degrees features the highest number of EVs, with 25 million pure EVs (PEVs), those that are 100% electric-powered, on our roads by 2050.

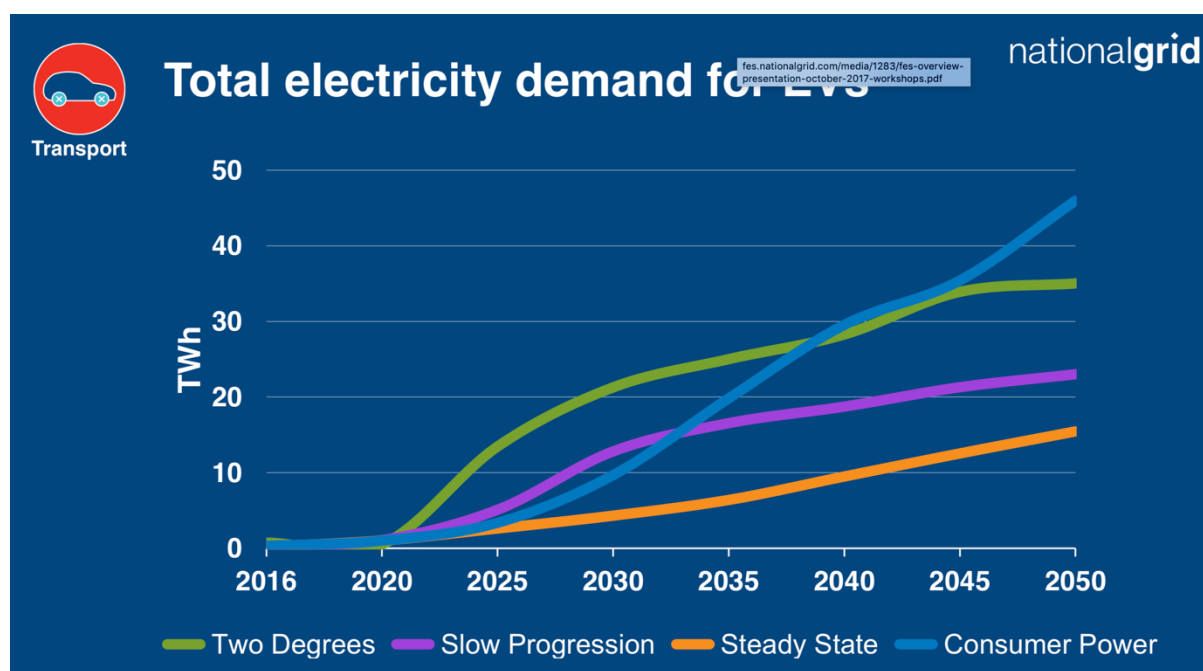
At the other end of the spectrum, Steady State sees the lowest growth, where both PEVs and Plug-in Hybrid EVs (PHEVs) each account for only 15% of car sales by 2050. The government's announcement, if it becomes law, will clearly accelerate the move away from our historical reliance on petrol and diesel cars."

The potential effect on electricity demand

Our FES analysis paints a contrasting picture of future annual demand from EVs.



Up to the late 2030s, the EVs in Two Degrees use the most power annually of all the scenarios. Beyond that point, the highest consumption is in Consumer Power, where consumers are driven by the desire for the latest technology. We estimate that by 2050, EVs in the Consumer Power scenario create an annual demand of 46TWh – or about 11% of 2050 national demand.



As the numbers of EVs increase, their peak time electricity demand is one of the challenges that will need to be met. For example, our Consumer Power scenario suggests that EVs will create an extra 18GW of demand by 2050 – that's equivalent to an extra 30% on top of today's peak demand.

You could argue that millions of motorists all needing to charge their electric vehicles would require lots of new power stations just to meet this surge in demand. But in fact this is where better consumer engagement and advances in technology both have a part to play.

Smart charging and switched on consumers

If every consumer chose to charge their vehicle after getting home from work at 5pm, as System Operator we would face runaway peak demand to manage. The consumer would still have the choice of when and how to charge. In reality, there is already diversity of demand. People arrive home at different times and have different routines, with only one in five expected to charge at peak times. It's a little bit like every home having a kettle, but we don't all make a cup of tea at the same time.

Solutions lie in a combination of incentives to encourage off-peak charging and smart systems that make the process of charging itself as simple and automated as possible. Consumers would likely be just a couple of clicks on an app away from getting the whole thing done with the minimum of fuss.

Where and how we will charge in future

There is a lot of debate about different models for charging EVs in future. Half of households in Great Britain don't have off road parking. This presents a very practical issue in terms of charging a vehicle at home!

In this year's FES analysis, we have assumed that 7kW chargers become the standard in people's homes, whereas in last year's FES we focused on 3.5kW – this reflects the direction in which manufacturers are moving.

We also assume that chargers will be smart-enabled – in other words they can talk to each other, helping consumers, if they would like to, and potential service providers manage demand in the most effective way.

The forecourt model is another option. We are all used to the concept of filling up the family car, even if the experience of negotiating the queue for the pumps is not always the most enjoyable.

Charging stations may well follow a similar set-up, although motorists would want to be able to charge their vehicles quickly and easily. (up to 350KW... !! See National Grid documentation on Electric Vehicle Charging)

Meanwhile, several companies are investing in 'flash battery' technology that could allow a vehicle to run for a long distance from a five-minute charge. If successful, this super rapid EV

charging could support the introduction of more forecourt charging sites. From a system operation perspective these super rapid charging sites would likely need some form of network reinforcement.

How quickly will technology advance?

If we take a step back for a moment and consider the speed at which the EV market is now developing, it's quite telling. Who knows how much battery technology might have progressed by 2040? Certainly, motorists will expect electric vehicles to be capable of broadly the same range and performance as their existing vehicle as technology matures.

And about rural areas, which are currently under-served by rapid charging points? Clearly, there is work to do on developing more comprehensive charging infrastructure to meet the needs of a larger electric fleet.

So, as we digest the implications of the government's announcement on a 2040 cut-off point for sales of petrol and diesel vehicles, there are many unanswered questions. We do, however, know the answer to one of them: "Are electric vehicles here to stay?" It's a simple "yes".

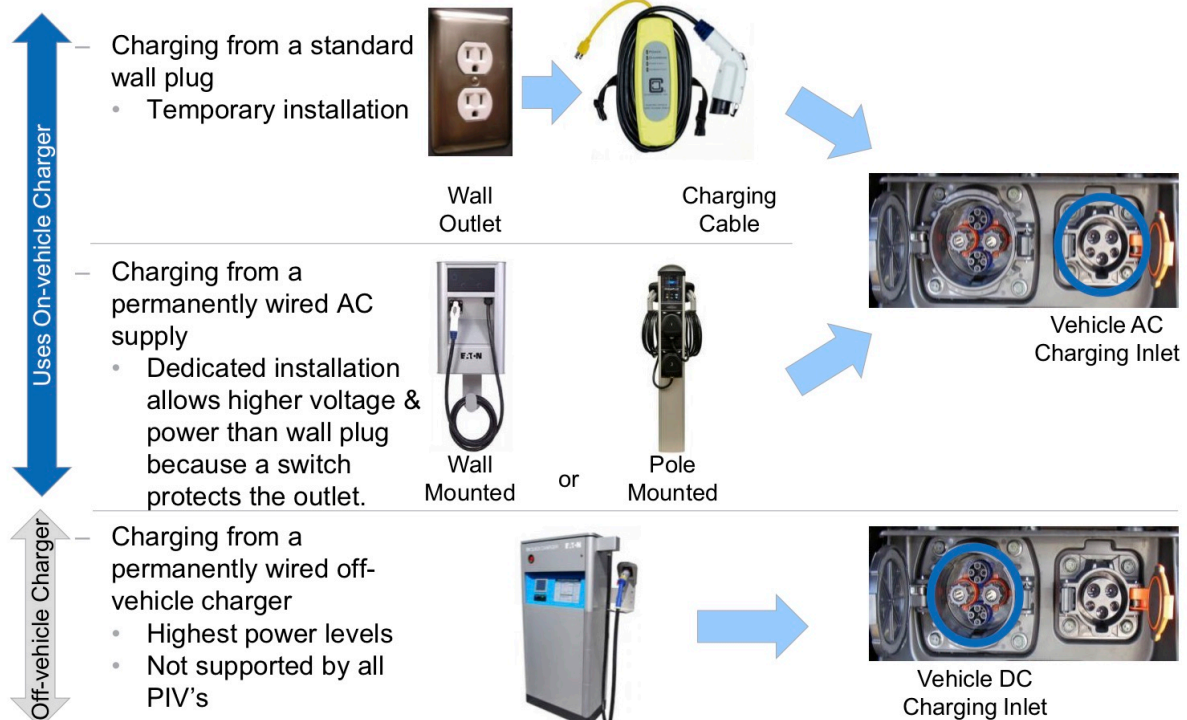
See National Grid documentation on Electric Vehicle Charging.....

Charging Electric Vehicles

Dr Owen Williams – University of Wales TSD:

PIV Charging Technologies

Overview of three types of charging connectivity for on-vehicle and off-vehicle chargers¹



¹ – Industry is developing wireless charging, but systems are still in the research phases and are not likely to be in a production vehicle for >5 years.

ARPA-E RANGE Kickoff

29 January 2014

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There are three main types of EV charging – **rapid**, **fast**, and **slow**. These represent the power outputs, and therefore charging speeds, available to charge an EV. Note that power is measured in kilowatts (kW).

Rapid chargers are one of two types – AC or DC [Alternating or Direct Current]. Current Rapid AC chargers are rated at 43 kW, while most Rapid DC units are at least 50 kW. Both will charge the majority of EVs to 80% in around 30-60 minutes (depending on battery capacity). Tesla Superchargers are also Rapid DC and charge at around 120 kW. Rapid AC devices use a tethered Type 2 connector, and Rapid DC chargers are fitted with a CCS, CHAdeMO or Tesla Type 2.

Fast chargers include those which provide power from 7 kW to 22 kW, which typically fully charge an EV in 3-4 hours. Common fast connectors are a tethered Type 1 or a Type 2 socket (via a connector cable supplied with the vehicle).

Slow units (up to 3 kW) are best used for overnight charging and usually take between 6 and 12 hours for a pure-EV, or 2-4 hours for a PHEV. EVs charge on slow devices using a cable which connects the vehicle to a 3-pin or Type 2 socket.

Comparison of charging power levels (and gasoline fueling)

(vehicle on-board charger &/or battery pack may limit actual power)



		Max. Voltage (Volts)	Max. Current (Amps)	Power (kW)	Range Gain (miles/hr) ^a	Fueling Time (% Drive Time) ^b
SAE J1772	AC Level I 	120 ^c (1 ϕ)	16	1.9	5.5	1280%
	AC Level II 	240 ^c (1 ϕ)	80	19	55	130%
	DC Level I 	500 DC	80	40	80 ^d	88%
	DC Level II 	500 DC	200	100	200 ^d	35%
IEC 62196-1	Mode 1 	250 (1 ϕ) or 480 (3 ϕ)	16	7.7	22	320%
	Mode 2 	250 (1 ϕ) or 480 (3 ϕ)	32	15	44	160%
	Mode 3 	500 (3 ϕ)	250	125	360 ^d	20%
	Mode 4 	600 DC	400	240	400 ^d	18%
	CHAdemo 	500 DC	100	50	100 ^d	70%
	Tesla Supercharger			120	340	20%
	Gasoline at gas station	@10 gal/min & 30 mpg		20,000	18,000	0.4%

^a – Assuming 350 W-hr/mile

^b – Assuming 70 mph average highway driving speed

^c – North American Limits

^d – Assuming 350V battery pack

- **Today's fastest chargers still slow our driving down by 20% or more for long trips**

There are obvious implications in terms of safety for 'fast charge' devices, but there are also problems for the battery itself while fast charging, since a lot of heat can be generated during charging and this can be very problematic for the battery of the vehicle.

See Paper on Fast Charging:

In the recent years, lithium-ion batteries have become the battery technology of choice for portable devices, electric vehicles and grid storage. While increasing numbers of car manufacturers are introducing electrified models into their offering, range anxiety and the length of time required to recharge the batteries are still a common concern. The high currents needed to accelerate the charging process have been known to reduce energy efficiency and cause accelerated capacity and power fade. Fast charging is a multiscale problem, therefore insights from atomic to system level are required to understand and improve fast charging performance. The present paper reviews the literature on the physical phenomena that limit battery charging speeds, the degradation mechanisms that commonly result from charging at high currents, and the approaches that have been proposed to address these issues. Special attention is paid to low temperature charging. Alternative fast charging protocols are presented and critically assessed. Safety implications are explored, including the potential influence of fast charging on thermal runaway characteristics. Finally, knowledge gaps are identified and recommendations are made for the direction of future research. The need to develop reliable onboard methods to detect lithium plating and mechanical degradation is highlighted. Robust model-based charging optimisation strategies are identified as key to enabling fast charging in all conditions. Thermal management strategies to both cool batteries during charging and preheat them in cold weather are acknowledged as critical, with a particular focus on techniques capable of achieving high speeds and good temperature homogeneities.

Now, back to burning Dinosaur Juice.....