

THE FUTURE FOR HYDROGEN TRAINS IN THE UK

Institution of
**MECHANICAL
ENGINEERS**

The challenges of decarbonising our energy system are becoming increasingly difficult. We have begun by addressing the easier options in the power industry, but with concerns about reducing air quality and pollution, the decarbonisation of our transport system is critical in meeting UK targets for emission reductions. When it comes to the rail industry, the Institution of Mechanical Engineers encourages greater electrification of the national rail network.

The Institution of Mechanical Engineers recommends:

- 1. That the UK Government rethinks the cancellation of electrification programmes and moves forward with a more innovative, and long-term approach, electrification rolling programme, that can create skills and careers, develop supply chains, and work with existing rail networks to manage projects.**
- 2. That the industry encourages the development and deployment of hydrogen trains and their fuelling and servicing facilities.** Creating and supporting demonstration lines and trains will help to de-risk the technologies and servicing relating to hydrogen fuels and trains.
- 3. That hydrogen train technology is developed in industrial areas where hydrogen production already occurs, and can support the wider transport system.** For example, as well as local trains, local hydrogen buses could be refuelled at an industrial site, and hydrogen could also be pumped into the gas grid to help decarbonise heat. Both the North West and the North East could support test beds. These test beds will support knowledge sharing across sectors, providing cost reductions in hydrogen fuel.

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BACKGROUND

With some recent electrification projects running significantly over budget, in the last year we have seen the Government cancel three different electrification schemes.^[1] Continental experience, and indeed that in Scotland, show that electrification does not have to be excessively expensive if there is a long-term programme of electrification that encourages skilled staff retention and application of standardised designs. The sporadic nature of electrification in the UK is shown in **Figure 1**.

The challenge of decarbonising and cleaning up rail emissions has not gone away with the cancellation of these schemes. Previous Transport Minister, Jo Johnson, has suggested using hydrogen trains as a replacement for diesel ones. Teesside and Cumbria have been identified by the Government as regions where we will see new hydrogen trains first. So what is the potential for hydrogen trains and what does the use of hydrogen as a replacement for diesel mean for the UK?

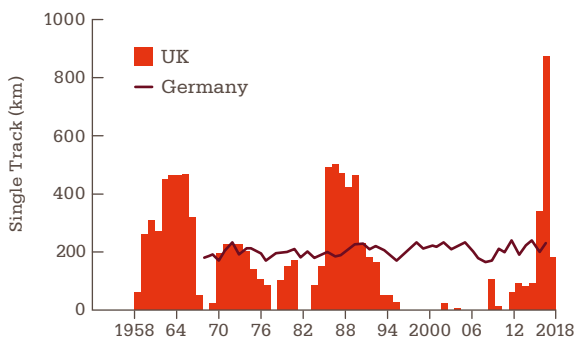
INTRODUCTION

Hydrogen is a fuel that can be used in an internal combustion engine as a replacement for fossil fuels such as oil and gas, and can also be used in a fuel cell battery. These options produce power for locomotives without producing greenhouse gas emissions and particulates, which contribute to air pollution and climate change. It is for these reasons that hydrogen is seen as a good alternative for trains operating outside the electrified rail network in the UK.

Although it is potentially part of the decarbonisation solution for railways, there is a wariness with respect to hydrogen fuel cell technology, where hydrogen's low volumetric energy density does not encourage rail traction applications when weight and space are critical design constraints in rail vehicle design. In addition, as explained below, if hydrogen is produced by electrolysis, it requires three times the energy across the whole system of an electric train.

Nevertheless, there is a concern that hydrogen trains will be used by funders as a reason to avoid future electrification. This fear should be eliminated at source, by ensuring a universal understanding that fuel cell traction should be viewed as an option only where long-term technical, environmental and/or economic factors make electrification a poor option. These relate to frequency of use, remoteness from electrical supply and physical constraints (including those of freight yards). On this basis, most lines in the UK should be electrified. Even the frequency of use measure is a grey area, specifically with respect to infrequently served branches of electrified mainlines.

Figure 1: Nature of rail electrification^[2]



HYDROGEN PRODUCTION

Hydrogen production and use can be seen in **Figure 2**, with the largest proportion of hydrogen being produced through steam methane reforming, with 96% of hydrogen produced using fossil fuels. In addition, the current uses of hydrogen are dominated by petroleum recovery and refining, and ammonia production, with less than 1% being used as a fuel for transport, power and heating, which are the areas being discussed today as potential hydrogen end-users.

The production of hydrogen raises questions about its role as a decarbonised fuel. **Table 1** provides details of the differences between 'brown' and 'green' hydrogen, with brown being unsustainable and very limited in its contribution to decarbonisation. Hydrogen as a fuel would, however, reduce particulate emissions and improve air quality.

Green hydrogen is mainly produced using electrolysis, and uses a DC current to split water into hydrogen and oxygen. This can cost 50% more than steam reforming, but is a low-carbon process if the electricity used is generated by renewables or nuclear power. Fuel cells reverse this process, using a catalyst to combine hydrogen with oxygen in the air.

Figure 2: Hydrogen Production and Consumption Globally^[3]

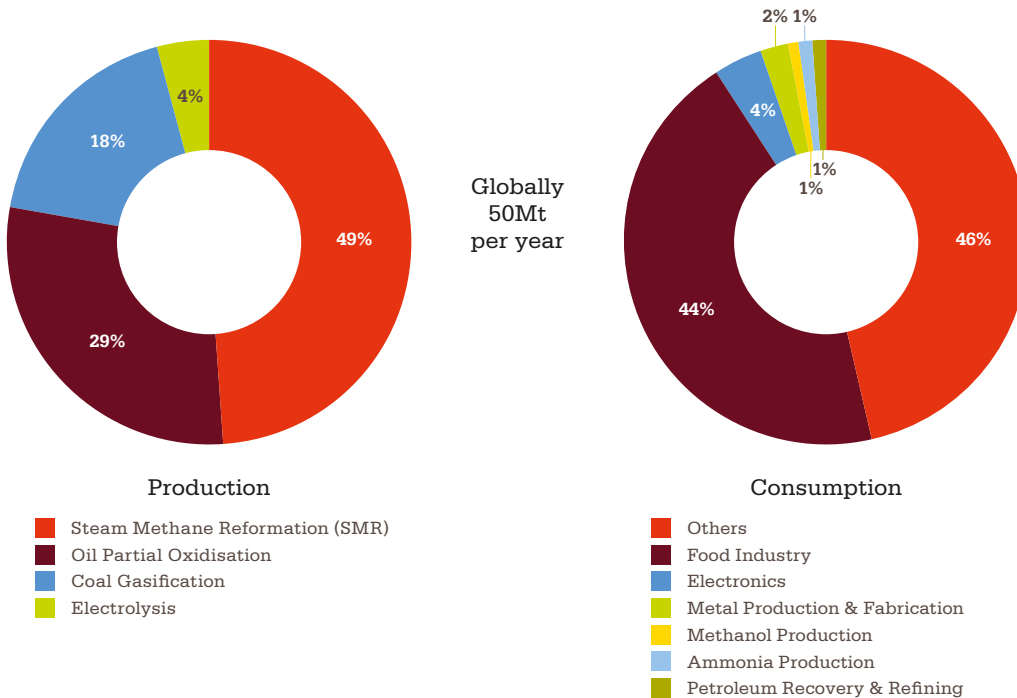


Table 1: Differences between 'brown' and 'green' hydrogen production

Brown Hydrogen (Produced unsustainably)

- Steam methane reforming – high temp process $\text{CH}_4 + \text{H}_2\text{O} (+\text{heat}) \rightleftharpoons \text{CO} + 3\text{H}_2$
- Coal gasification – process of producing syngas – a mixture consisting primarily of CO , H_2 , CO_2 , CH_4 and water vapour (H_2O) – from coal and water, air and/or oxygen.
- Oil partial oxidation – fuel-air mixture is partially combusted in a reformer, creating a hydrogen-rich syngas.

Green Hydrogen (Produced sustainably)

- Electrolysis of water using renewable power – splitting of water into hydrogen and oxygen using an electrical current
- Steam methane reforming with carbon capture and storage techniques
- Gasification of biomass and biogas to produce syngas
- Fermentation of biowastes to produce H_2 , CO , CO_2

SAFETY

The use of hydrogen as a fuel on a rail vehicle, will have to comply with applicable legislation, including Technical Specifications for Interoperability (TSI). Compliance with TSI has already been demonstrated by passenger operation in Germany, but this will have to be reviewed for specific UK installations. The design will also have to comply with a risk assessment, which will ascertain the risks with this design and how they have been appropriately mitigated.

HYDROGEN CLUSTERS

Hydrogen is used in many industries in the UK, and is often located in industrial areas with other processes such as ammonia production, methane extraction and pipelines, gas storage and petroleum refining. This offers the option to utilise green hydrogen production in these areas to supply an existing market. This could include using steam methane reforming with CCS, or electrolysis of water on an industrial scale using renewables or nuclear power, as well as extracting hydrogen as a by-product of other industries. The replacement of brown hydrogen with green will stimulate the market and supply chain, as well as lead to wider possibilities for reducing carbon usage.

The overall efficiency of a hydrogen train is about a third that of an electric train, so on an intensively used railway it may be better to feed electricity directly into a train, instead of using it to create hydrogen. But creating hydrogen clusters around industry where hydrogen is produced could be a solution for localised transport systems. For example, trains and buses operating near industries where hydrogen is produced could use hydrogen as a fuel, as production, storage and refuelling would be nearby, reducing fuel distribution and transport costs.

ELECTRIFICATION

The current situation for rolling stock operating on UK railways, is that they operate using either electricity or diesel. Electric-powered trains are AC or DC from the fixed electrified infrastructure feeding traction motors connected to the wheels of the train. Diesel trains use an on-board engine that powers the axles of the train, or generates electricity to run electric motors in diesel-electric trains. Fully electric-powered trains running on the fixed electrified network are the most efficient, cost-effective and environmentally friendly. For example, on its West Coast services, the traction cost of diesel for Virgin trains is four times that of electricity.^[1] One reason for this is that, unlike self-powered vehicles, electric traction can utilise the huge amount of energy generated during braking, and feed it back into the train power system.

With its high initial capital cost, electrification is best suited for busy routes. Many countries have a high percentage of their rail network electrified. These include the Netherlands (76%), Italy (71%) and Spain (61%). In the UK just 42% of the network is electrified, although electric trains comprise 72% of the UK passenger fleet. The railway sector in the UK is now in the position that it is currently managing ageing diesel-powered trains, some of which were made prior to 1993 and are set to remain in service for another ten years or more.

Electrification projects have been cancelled across the UK, with cost being cited as the reason. Electrification, like other major infrastructure projects undertaken sporadically, will be expensive if not treated as long-term rolling programmes. This is because every project requires new skills development, new supply chains and new logistics and project management. If electrification were conducted as an ongoing activity, we would not lose the skills and supply chains needed each time. Prior to the Great Western electrification scheme, the last major electrification programmes were completed in the 1980s and early 90s.^[4]

TRACTION POWER REQUIREMENTS

A train's power ranges from 450KW for a two-coach local train to 6MW for a 125mph 11-coach electric inter-city train. The respective power-to-weight ratios of these trains are 5.7KW and 10.5KW per tonne. Commuter trains do not necessarily travel at high speeds, but require high power for the acceleration needed to operate a passenger service with frequent stops to an acceptable timetable. An electric multiple unit (EMU) typically has twice the acceleration of a diesel multiple unit.

A UK diesel freight locomotive of typically 2,500KW might haul a train of 2,000 tonnes. Freight services and depots also require shunting locomotives to marshal trains. These need a high tractive effort to move heavy loads, but operate only at low speeds, so require a low-powered engine of, say, 250KW.

As of March 2017, Britain had 14,000 rail passenger vehicles, of which 72% were electric trains and the rest self-powered. There are also 800 freight locomotives, of which 16% are electric. In addition, there are 180 shunters.^[1]

Table 2: Engine power options

Train Technology	
Diesel	Diesel trains use on-board engines that power the axles of the train, or generate electricity to run electric motors in diesel-electric trains.
Electric	Electric-powered trains are AC or DC from the fixed electrified infrastructure feeding traction motors connected to the wheels of the train.
Bi-Mode	Designed to operate on both electrified lines and non-electrified lines. Those currently being introduced on Great Western and East Coast routes are able to switch between the electric-powered mode and on-board diesel engines. However, while flexible, the electric-diesel bi-mode train creates emissions when operating in diesel mode, has higher fuel, capital and maintenance costs than pure electric trains, and is less powerful when working in diesel mode (8.6KW/tonne) compared with electric mode (11.2KW/tonne). ^[5] Bi-mode trains offer a solution to non-electrified lines and reduce the requirement to invest in electrification, but do not provide the optimum performance or offer the most efficient or environmentally friendly solution.
Hydrogen	Powered in a similar way to electric trains, they use a fuel cell that provides the electricity from the controlled reaction of hydrogen with air. The fuel cell works by ensuring the positively charged hydrogen ions pass through an electrolyte to a cathode, and hence provide electrical power in an external circuit. The emissions from this process are water and heat. One key difference between the fuel cell and conventional electric train, is that fuel cell-powered trains are less efficient when it comes to rail traction; they are similar to diesel-powered trains at about 30%, although this may increase depending on how the hydrogen is produced, transported and stored. ^[6] The traction energy efficiency depends on a number of factors, from air resistance and inertia to comfort functions and efficiency losses.

OPERATIONS

Typical efficiencies for electrolysis and fuel cells are respectively 68% and 52%. Compressing hydrogen for storage, typically at 350bar, requires 6% of its chemical energy. The overall cycle efficiency from multiplying all these efficiencies is 33%. Hence hydrogen traction requires 3KW of electricity to deliver 1KW of power to the wheel. An electric train has no on-board energy conversion, so needs only 1.2KW.

This low overall cycle efficiency potentially undermines the green credentials of hydrogen trains, as they require 2½ times the electrical energy of a comparable electric train, especially if hydrogen is delivered by the much cheaper CO₂-producing reforming process. However, if otherwise surplus overnight (eg wind-turbine) generating capacity is used to produce and store hydrogen, this low efficiency is not an issue, due to the availability of this energy source. Used in this way, hydrogen production also addresses intermittency issues associated with electrical generation from renewables.

A further constraint is hydrogen's low energy density. At 350bar, the volumetric energy density of hydrogen is 4.6MJ/litre, compared with 35.8MJ/litre for diesel. So a hydrogen train requires fuel storage eight times the size of a diesel train's fuel tank. For this reason, high-powered, long-range hydrogen traction would require addition vehicles with hydrogen tanks, which would reduce the number of passengers or freight on the train.

If hydrogen is not produced at a refuelling site, then it has to be transported to that location. There are options for this: hydrogen can be moved in compressed-gas cylinders or cryogenic tankers; there is also potential to use hydrogen pipelines, and possibly in the future hydrogen could be transported using a repurposed gas distribution grid that we currently use for natural gas. Current applications under consideration for hydrogen train deployment, benefit from areas where hydrogen is readily available from either petrochemical industries or using renewable energy supplies for electrolysis.

RECOMMENDATIONS

Fuel cells should be considered as part of the train decarbonisation strategy, for routes where electrification is sub-optimal, such as low-density rural routes. As trains can be serviced at one end of the route, an extensive hydrogen network is unlikely to be required. The technology should be considered as possibly best applied on rural routes. Cost and efficiency will be key factors, and the impact on the National Grid will be notable.

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