WHY RAIL ELECTRIFICATION?

IN COLLABORATION WITH

Railway Industry Association

The voice of the UK rail supply community

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As part of the
RailDecarb21 campaign

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#RailDecarb21

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Preface

I am very pleased that the authors asked the Railway Industry Association (RIA) to collaborate with them on this report as it both complements and extends RIA's own work, including the Electrification Cost Challenge Report published in 2019 and our recently launched RailDecarb21 campaign.

In asking the question 'Why Electrification?' this report considers analytically and objectively all forms of rail decarbonisation. It shows that battery and hydrogen trains will have an important role, concluding that electrification is the optimal choice for the majority of rail lines on the network. It also, perhaps for the first time, assesses the embodied carbon impacts of electrification, showing that the carbon emitted in 'putting the wires up' is quickly repaid back by emissions no longer being produced from diesel trains. As the report details, battery and hydrogen trains have an important and complementary role but, crucially, are not going to be able to develop to the point where they displace electrification.

RIA has consistently called for a rolling programme of electrification and fleet orders of low carbon self-powered rolling stock. At first this was because electrification is more efficient, higher performing, and has lower life cycle costs on intensively used railways. But more recently making the case for electrification has become even more essential, with the UK committing to achieve net-zero carbon by 2050 and the cancellation of a number of electrification projects in 2017 following cost overruns on some projects, most notably the Great Western Electrification Programme.

These cancellations led to RIA publishing our Electrification Cost Challenge[1] in 2019, demonstrating that 75% of the projects from 2014 to 2019 had been delivered efficiently but that the successful projects were overshadowed by poor delivery on Great Western, with Government losing confidence in the ability of Network Rail and the wider industry to deliver as a consequence.

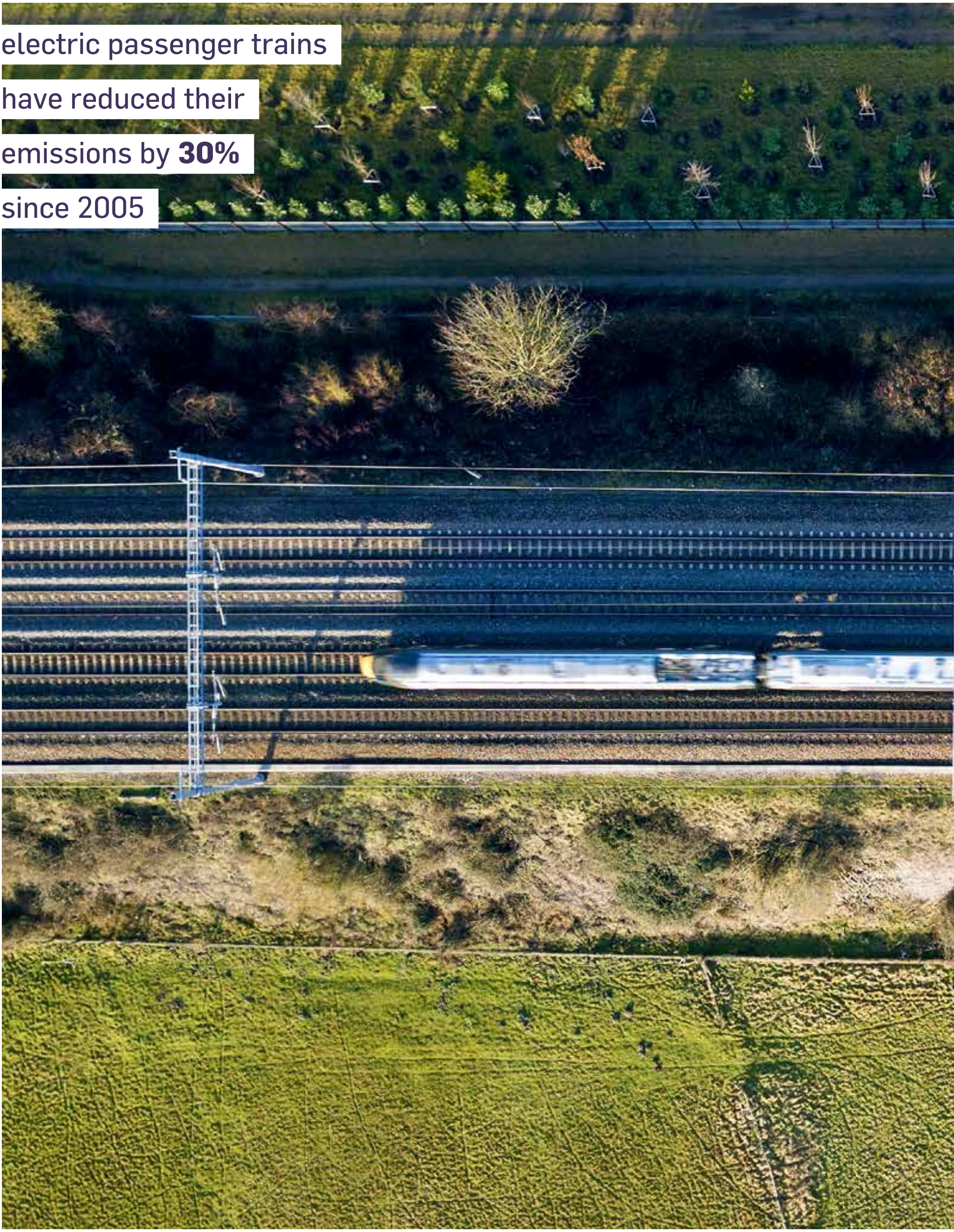
The most significant lesson from the report was the need for a rolling programme of electrification - a steady volume of activity over the long term - which allows the retention and development of the specialist skilled resource for overhead line work. In RIA's view, the root cause of the problems in 2014-19 was the 20-year hiatus in UK electrification before 2014.

In the meantime, suppliers have been hard at work developing and proving low carbon hybrid, battery and hydrogen powered trains, such that by 2021 we have credible alternatives to diesel passenger trains up to 100mph, from a range of manufacturers. Crucially, however, whilst these new technologies will have a place on the network, we can't let them be used as a reason not to electrify. As the Transport Committee's[2] March 2021 'Trains Fit For the Future' report says 'electrification is the only immediately viable decarbonisation option for most of the network, not least because the alternatives are not suitable for freight and high-speed services due to their high energy demands.'

This report provides further evidence for the view that rail decarbonisation will simply not happen without electrification. And we join the Transport Select Committee in calling upon the Department for Transport to start the electrification programme as soon as possible, rather than wait for the next Control Period in 2024. There is good reason to start now - one tonne of carbon saved in 2021, will be 29 tonnes saved by 2050. So let's get on with it.

David Clarke
Technical Director
Railway Industry Association

electric passenger trains
have reduced their
emissions by **30%**
since 2005



Foreword

Werner von Siemens demonstrated in 1879 that infrastructure-supplied electric trains would transform the performance of the railways by eliminating onboard conversion of chemical energy into tractive power. Diesel traction, and before that coal, provides only a restricted operating range and limited tractive effort, while emitting pollution at the point of use. Trains on overhead and third rail electrified railways, by contrast, do not need refuelling, their maintenance and running costs are much lower, they are more efficient and, most importantly, their performance is only limited by the capability of the supply.

Today's high-speed railways, intensive suburban services and high-capacity metro operations are only possible with electric trains. Their high acceleration rates result in lower journey times or allow more stops to serve the market better. Freight also benefits, thanks to longer trains requiring fewer paths. Better acceleration and higher speeds improve integration with passenger services.

Electrification is a future-proof technology. Electric trains require neither inefficient on-board power plants nor on-board energy storage involving multiple inefficient energy conversions. Electric energy can be supplied from sources with strong 'green' credentials, with modern inverter-based traction supplies able to cope with distributed generation, e.g. wind and solar. Battery traction is likely to have a role in applications where electrification is not viable but comes into its own where part of a route is electrified.

Network Rail's Traction Decarbonisation Network Strategy (TDNS) report concluded, in July 2020, that railway decarbonisation requires a large-scale electrification programme and that this has a good business case. This recommendation is also in line with commitments to electrify more railway lines in the Government's Ten Point Plan for a Green Industrial Revolution. However, the UK Government is yet to respond to the TDNS report. Recent comments downplaying electrification, for example, suggest that it might be possible to leapfrog overhead line technology altogether. This indicates a lack of awareness of its inherent benefits.

The industry has a responsibility to explain clearly to decision makers the benefits of electrification and, perhaps more importantly, the nature of traction power and why electric traction is future-proof.

I commend this report. The executive summary provides the main findings, whilst the body of the report provides the evidence base to substantiate these. I concur with the content and conclusions of this report and I am certain that it represents fairly the view of engineers throughout the industry. I hope that Government decision-makers concerned with railway investment have the opportunity to read this report and find it useful.

Professor Felix Schmid
Chair of the Railway Division of the IMechE
Professor emeritus of Railway Systems Engineering
at the University of Birmingham

EXECUTIVE SUMMARY

1

Current battery and hydrogen trains require, respectively, 21 and 12 times the storage volume of a diesel tank

Although Britain has reduced its carbon emissions by 40% since 1990, there has been no reduction in overall transport emissions, yet electric passenger trains have reduced their emissions by 30% since 2005. Rail transport has a high energy efficiency with correspondingly low carbon emissions. Per tonne kilometre, HGVs have nine times the emissions of rail freight.

Hence, the rail sector can do much more for UK transport decarbonisation than just eliminate its own emissions. A modal shift of 4% of passengers and 4% of freight transport to rail would save more carbon than the rail sector's current total emissions. To achieve this modal shift, the rail network needs high-performance traction to attract traffic from road and air. To be able to accept this traffic, the network needs capacity enhancement.

If the transport sector is to decarbonise, it has to abandon the use of petroleum, even though it stores energy highly efficiently. The only high-power energy source offering potentially net-zero carbon is electricity. This can be transmitted over large distances but only to fixed locations and should be used as it is generated, since storage requires inefficient energy conversions.

Electric trains collect electricity on the move from their fixed current collection systems. All other zero-carbon vehicles need to be 'fuelled' using electricity converted into another form of energy for on-board storage and converted back into electricity when required. Energy is always lost during such conversions. Batteries store energy by means of a reversible chemical reaction while an electro-chemical process creates hydrogen from electricity. Current battery and hydrogen trains require, respectively, 21 and 12 times the storage volume of a diesel tank.

Thus, electric trains, which simply supply electricity from the national grid to their motors, will always provide the most powerful and efficient railway traction, with the lowest operating cost. The other traction options have these limitations:

- **Diesel trains' heavy engines limit the power available, whilst an electric train's power is only limited by the electricity it can receive from the overhead line.**
- **A battery pack storing the same energy as a typical diesel rail passenger vehicle would weigh an extra 40 tonnes and so double the weight of the vehicle.**
- **A proposed UK hydrogen passenger train needs a quarter of its interior space to store the gas and then only stores about a quarter of the energy of an equivalent diesel train.**
- **Storing hydrogen for a freight locomotive would take up more space than the locomotive itself - a battery freight locomotive would require batteries weighing 350 tonnes to achieve the same range and performance as a diesel locomotive.**
- **Typical comparative estimated efficiencies are: electric – 80%, battery – 65%, hydrogen – 25%,[3] diesel – 25%.[3]**
  Note: Appendix 3 has a bottom up analysis which estimates the efficiency of a hydrogen train to be 34%

Network Rail's Traction Decarbonisation Network Strategy (TDNS) concluded that the required net-zero rail traction mix should be: electrification – 86%, hydrogen – 9% and batteries – 5%. However, more battery and hydrogen trains will be required before 2050 as much of the current diesel fleet will be life-expired before then.

electric trains are the only net-zero carbon option for freight

Studies have shown that an electrification programme of around 10% of that recommended by TDNS would enable about 70% of rail freight to be electrically hauled

The TDNS also shows that electric trains, which are twice as powerful as diesel locomotives, are the only net-zero carbon option for freight. They also provide greater freight and passenger capacity by reducing the speed differential between passenger and freight trains. Currently, electricity provides only 4% of UK rail freight's energy requirement, compared with 56% in continental Europe. Studies have shown that an electrification programme of around 10% of that recommended by TDNS would enable about 70% of rail freight to be electrically hauled.

Electrification is also a good investment, both financially and in respect of carbon, as the emissions from the electrification work are recouped from traction carbon savings within a few years. Its benefits also include:

- Lifetime vehicle operational savings of, typically, £2.5 million.
- Increased revenue and better utilisation, thanks to journey time reductions offered by greater speeds and higher acceleration rates.
- Greater freight train speeds and tonnage.
- Increased capacity and timetable resilience.

The laws of nature make electrification a future-proofed technology that is a good investment, offering large passenger, freight, and operational benefits

Thus, electric trains will attract modal shift from less carbon friendly transport and provide the required capacity to accommodate it. The TDNS study concluded that, with these benefits, its recommended electrification programme has a positive business case when delivered at the capital costs of current schemes. However, some recent schemes came in significantly over budget, and so it is understandable that some might consider electrification to be unaffordable.

Much has been done to learn from these costly schemes, as explained in the Railway Industry Association's Electrification Cost Challenge Report. One key factor was that, when these schemes started, the industry had largely lost its skills base, as there had been hardly any new electrification for 20 years. Ramping up skills and capability to deliver a particularly large electrification programme then took time. In addition, innovations have reduced electrification costs and have allowed more recent schemes to be delivered in a cost-effective manner.

Efficient electrification requires a steady rolling programme, delivered by experienced teams. Given the size of this programme, a start needs to be made now if the 2050 net-zero carbon target is to be met. Furthermore, hard-won lessons will be lost unless further electrification schemes are approved and started soon.

Evidence does not support the view that electrification is unnecessary, thanks to hydrogen and battery systems improving rapidly: hydrogen trains are inherently less efficient than electric trains, due to the physical properties of the gas. Expert opinion predicts that battery capability might double by 2035. *Yet, whilst this might affect the hydrogen / battery traction mix required for decarbonisation, it is unlikely to change significantly the requirement for electrification.*

The laws of nature make electrification a future-proofed technology that is a good investment, offering large passenger, freight, and operational benefits. Furthermore, railways cannot achieve net-zero carbon emissions without a large-scale electrification programme. Evidence that conclusively substantiates these, and other statements, is contained in this document.

SYNERGIES BETWEEN UK DECARBONISATION AND RAIL DECARBONISATION

2

Rail's greatest contribution to UK decarbonisation is likely to be from modal shift to rail

The Climate Change Act gives the UK a legally binding target of achieving net-zero greenhouse gas (GHG) emissions by 2050. Since 1990 Britain has reduced its GHG emissions to 58%[4] of 1990 levels. Most of this reduction was from power generation due to the increasing use of renewables and the virtual elimination of electricity generated from coal.

In its report *"Net Zero – The UK's contribution to stopping global warming"*, the Climate Change Committee (CCC) concludes that widespread electrification of transport and heating in buildings is needed. The electrification of transport to achieve net-zero carbon emissions requires all vehicles to be powered by batteries, hydrogen or, for railways, direct electric traction.

Whilst the CCC report considers that biofuels have a role in UK decarbonisation, it concludes that genuine low-carbon biofuels are a limited resource and so recommends they should not be used for surface transport for which there are other decarbonisation options.

To meet the demand for this widespread electrification, the CCC considers that by 2050, there needs the be a quadrupling of renewable electrical generating capacity as shown in Appendix 1. It also considers that there needs to be at least a tenfold increase in hydrogen produced from zero-carbon sources. Although most of this would be required for heating, some would be required for transport of which a large proportion would be needed for heavy goods vehicles.

The CCC also considers that car mileage should be reduced by 10% by a shift to active travel and public transport. It also considers the need for a shift from domestic aviation to high-speed rail and to similarly reduce HGV mileage.

This is considered in Appendix 2 which shows the carbon savings for various modal shift scenarios and their resultant increase of (pre-Covid) levels of passenger and freight rail traffic. In one scenario this shows that a 4% transfer from cars to rail and 20% transfer from domestic flights to rail would save 1.9 million tonnes of carbon dioxide equivalent gases (CO_2e) but would increase passenger rail traffic by 36%. A 4% transfer of road freight to rail would save 1.4 million tonnes CO_2e and increase rail freight traffic by 35%.

A 4% transfer of road freight to rail would save **1.4 million tonnes CO_2e**

Class 88 — The class 88 locomotive is a dual mode locomotive that can take power from overhead line equipment or be powered by its own diesel engine. Its power output in electric mode is 4 megawatts whilst its diesel power is only 0.7 megawatts. Hence its diesel power is only sufficient for low-speed dedicated freight lines or movements within a freight terminal.

The combined savings of these passenger and freight modal shift scenarios would be 3.3 million tonnes which is equivalent to the current GHG emissions from rail traction. *This indicates that rail's greatest contribution to UK decarbonisation is likely to be from modal shift to rail. However, to accept this modal shift the rail network needs to increase both its capacity to accept it and have sufficient high-performance electric traction to attract traffic from other modes. This is particularly true for freight.*

RAIL DECARBONISATION — PERMANENT SOLUTIONS

3

Electric traction offers significant benefits to passengers, freight customers and the taxpayer over diesel traction. Its performance should be the benchmark for a future railway

As described in Appendix 1, the only zero-carbon traction alternatives are electric trains, hydrogen, and battery traction. Before considering hydrogen and battery traction, it is instructive to compare electric and diesel traction. Electric traction offers significant benefits to passengers, freight customers and the taxpayer over diesel traction. Its performance should be the benchmark for a future railway.

3.1 Comparing diesel and electric traction

Electric trains are generally three times more energy-efficient than diesel trains and are much more powerful (Figure 11, Appendix 3). Yet in the UK diesel trains operate over many intensively used routes and almost all freight services are diesel powered. As a result the carbon emissions from Britain's railways are amongst the world's worst, as shown in Appendix 4.

Electric traction is more efficient, more powerful, lighter, healthier, and cheaper to operate than diesel traction for the following reasons:

- **An electric train's power is primarily limited only by the current that can be drawn from the overhead line or third rail whereas a diesel train's power is limited by the size of its engine and, notably, its ability to cool the engine.**
- **Diesel engines require energy to move the weight of their power plant and unused stored fuel.**
- **The size of this diesel engine is limited by the available space.**

- Diesel engines have unavoidable energy losses as they convert the chemical energy in fuel, first into heat, then electricity, and finally into motion (2nd law of thermodynamics). Diesel trains are also heavier and more expensive to maintain than electric trains.
- The engine also has to power the train's hotel load and auxiliary machines, whereas electric trains can simply draw that extra power from the overhead line or third rail.
- When braking, electric trains use the train's kinetic energy to generate electricity and feed it back into other trains or the national grid. This is known as regenerative braking and recovers typically 20% of a train's electricity consumption[5]. It also almost eliminates particulate emissions from brake pads.
- Electric trains have no engine emissions which is a particular health hazard at some stations and is increasingly unacceptable with the introduction of city clean air zones.

Electric trains are generally three times more energy-efficient than diesel trains

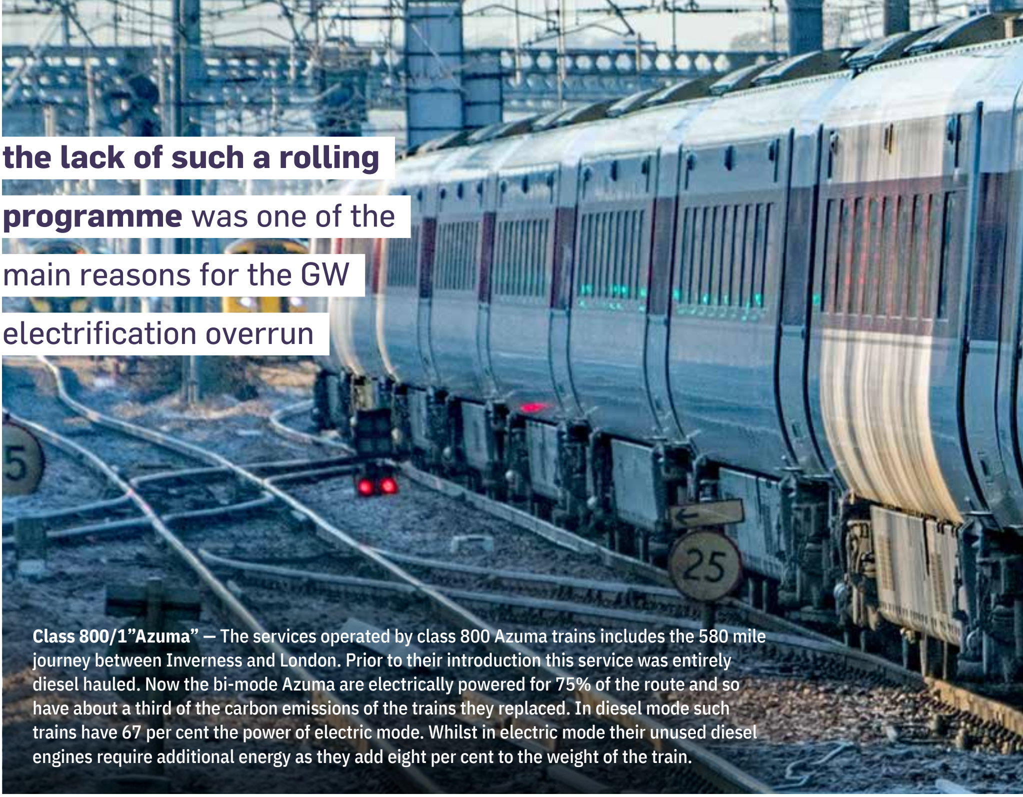
Electric trains can also take advantage of the greening of the grid. Between 2005 and 2019 the carbon intensity of the national grid was reduced from 724 to 274 tonnes CO_2e per GWh[6]. UK government plans are for British power generation to be net-zero by 2050. Once this is achieved electric trains will also have net-zero carbon emissions.

Figure 1[7] shows that, between 2009 and 2019, the CO_2 emissions from electric passenger vehicles have halved and that a diesel passenger vehicle has more than four times the carbon emissions of an electric vehicle.

		2009/10	2019/20
ELECTRIC	Fleet size - vehicles	8,751	11,503
	Electricity use , million kWh	3,061	4,186
	CO_2e ktonnes CO_2e	1,592	1,086
	CO_2e grams per kW	520	259
	CO_2e tonnes per vehicle	182	94
DIESEL	Fleet size - vehicles	3,896	3,355
	Diesel use, millions litres	482	476
	ktonnes CO_2e	1,267	1,313
	CO_2e kg per litre	2.63	2.76
	CO_2e tonnes per vehicle	325	391

Figure 1 – CO_2 emissions comparison between diesel and electric passenger vehicles from 2009 to 2019

the lack of such a rolling programme was one of the main reasons for the GW electrification overrun



Class 800/1"Azuma" — The services operated by class 800 Azuma trains includes the 580 mile journey between Inverness and London. Prior to their introduction this service was entirely diesel hauled. Now the bi-mode Azuma are electrically powered for 75% of the route and so have about a third of the carbon emissions of the trains they replaced. In diesel mode such trains have 67 per cent the power of electric mode. Whilst in electric mode their unused diesel engines require additional energy as they add eight per cent to the weight of the train.

3.2 Electrification costs and benefits

As shown in Appendix 3, *electrification saves lifetime costs of around £2 to £3 million per passenger vehicle.* The economic advantages of electric trains can be summarised as:

- Higher acceleration[8] and braking due to lower weight and ability to exceed rated power for short periods – meaning greater passenger capacity on routes with frequent stops and increased ability to recover from delays.
- Substantially higher freight haulage capability than with diesel locomotives, and attendant reduced freight journey times[9].
- Lower rolling stock capital cost[10].

- Lower rolling stock operational costs, due to fuel costs[11].
- Lower rolling stock maintenance costs[12 13], due to the much smaller number of moving parts and the requirement to overhaul diesel engines regularly to 'as new' condition.
- Greater train reliability[14], for the same reasons as above.
- Smaller fleet requirements due to increased reliability, since fewer trains are out of service for maintenance.
- Reduced health and environmental impact from diesel engine idling, particularly at stations, and noise.
- Lower track maintenance costs, driven by lower track forces from lighter power units.

Electric trains are also cleaner, and their more powerful traction provides faster journeys, better timetable resilience, greater rail capacity and increased freight train loads. As a result, Network Rail's Traction Decarbonisation Network Strategy concluded that, for most routes, there is a positive business case for electrification at current delivery costs.

The Rail Industry Association Electrification Cost Challenge report shows that the majority of CP5 Projects were delivered efficiently. However, this was not the case with Great Western and other electrification schemes of that time that incurred significant cost overruns. This resulted in the cancellation of electrification schemes as Government lost faith in the rail industry's ability to effectively deliver electrification.

One of the main reasons for such cost overruns was that, after almost 20 years with hardly any new electrification schemes, the rail industry had to rapidly ramp up its ability to deliver a large electrification programme as shown in Figure 2. Other reasons for these cost overruns and the lessons from them are detailed in the Railway Industry Association's Electrification Cost Challenge report[15]. This also highlighted the benefits of a continuous programme of electrification which keeps experienced teams together.

In Denmark and Germany where electrification has been delivered as a rolling programme (Figure 2), typical costs are circa £1 million per single track kilometre (stk). This compares with £2.2 million per stk for the Great Western electrification and between £0.75 and £1.5 million per stk for current UK schemes[15].

Indeed, the lack of such a rolling programme was one of the main reasons for the GW electrification overrun together with an overly demanding specification. After 20 years with few electrification schemes, the industry had largely lost its skills base and with this, the knowledge of best practice from successful British Rail schemes. As a result, it faced the huge challenge of rapidly ramping up its ability to deliver the large electrification programme shown in Figure 2.

Since the GW electrification, more recent electrification programmes have been delivered to cost and budget. Furthermore section 5.5 shows that there is significant potential to reduce the cost of future schemes from innovations that avoid the significant costs associated with bridge reconstructions and provide a more cost-effective electrical supply.

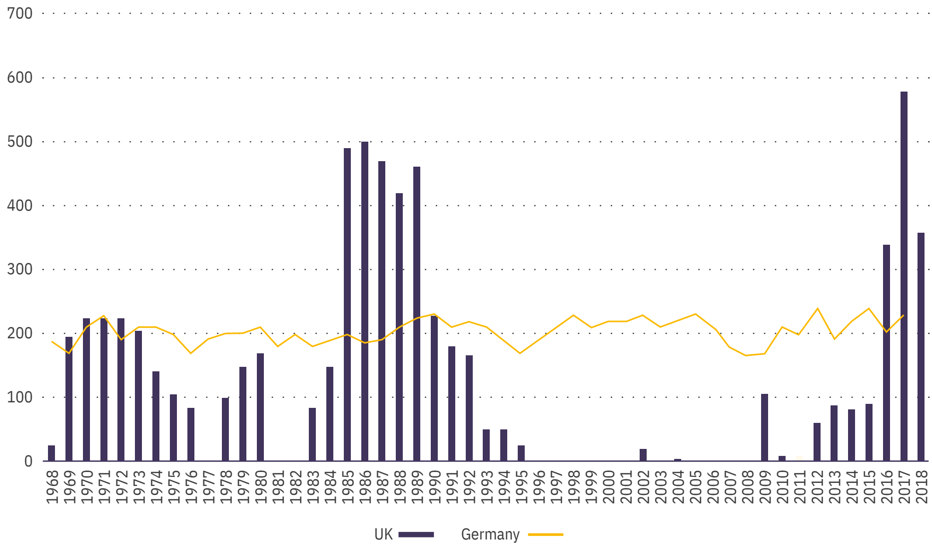


Figure 2 Historic delivery of UK and German electrification – single track kilometres (RIA Electrification Cost Challenge Report Figure 10, Noel Dolphin)

Class 180 — The large-scale use of diesel power such as this class 180 unit on intercity trains is one of the reasons why diesel is a much higher percentage rail traction energy than in other countries. As a result the UK rail has one of the world's worst railway carbon emissions record.

3.3 **Embodied carbon**

Whilst electrification offers significant operational carbon savings, these need to be balanced against the carbon emissions from the electrification work.

Network Rail's TDNS used the RSSB Rail Carbon Tool to estimate that the average carbon embodied in a single route kilometre of electrified railway is 680 tonnes CO_2e or 340 tonnes CO_2e per single track kilometre (stk). The embodied carbon cost of the 13,040 stk programme recommended by Network Rail's TDNS is therefore 4.43 million tonnes CO_2e.[16]

The carbon savings from this electrification work can be estimated from the difference between current total electric and diesel train emissions and that TDNS recommended electrification of 86% of the unelectrified network.

ORR data table 6105 shows that the 2019-2020 emissions of diesel passenger and freight trains were a total of 1.79 million tonnes of CO_2e. Figure 1 shows that the respective average carbon emissions of electric and diesel passenger vehicles in 2019-20 were 94 and 391 tonnes CO_2e per vehicle respectively. Hence an electric vehicle has 24% of the emissions of a diesel vehicle. Thus, replacing a diesel fleet with an electric fleet would give a 76% emission saving.

The estimated savings from the recommended TDNS electrification programme are therefore: 1.79x0.76x0.86 = 1.17 million tonnes CO_2e. This shows that embodied electrification carbon would be paid back in an estimated four years.

Given the short payback period derived from this estimate, and that electrification will offer carbon savings for many years, it is reasonable to conclude that the carbon benefits of electrification far outweigh the carbon cost of its provision.

3.4 **Self-powered alternatives to diesel traction**

Self-powered trains have a lower efficiency than electric trains, which use electricity as it is generated. Instead, they must store energy which adds to the train's weight. As electrical energy cannot be stored, it needs to be converted into another type of energy and then converted back to electricity when required. Energy is lost every time it is converted from one form to another. Within a train's constrained space, the only practicable storage options are chemical energy in batteries or hydrogen produced by electricity.

	By Volume		By Weight	
	MJ/litre	Storage Volume (x diesel)	MJ/kg	Storage Weight (x diesel)
Diesel	36		43	
Hydrogen (at 700 bar)	4.8	7.5	71[2]	0.6
Hydrogen (at 350 bar)[1]	2.9	12.4	71[2]	0.6
Battery pack – current	1.7	21.2	0.7	61.3
Battery pack – 2035	2.6	13.8[3]	1.0[3]	42.9

[1] Does not take account of inefficient storage of cylindrical tanks
[2] This does not include weight of tank which would be of order of 750kg
[3] Expert prediction by Advanced Propulsion Centre

Figure 3a – Comparative energy densities of diesel, hydrogen, and batteries

Hydrogen trains have an energy efficiency of about
34%

Figure 3a[17] shows that, to store the same amount of energy, hydrogen (currently stored on trains as a compressed gas at 350 bar, section 5.2 considers other options including 700 bar) and batteries require 12 and 21 times respectively more space than that of a diesel tank. It also shows this would also require batteries that weigh 61 times the weight of the diesel tank. Furthermore, the requirement to store hydrogen in cylindrical high-pressure cylinders is an inefficient use of storage space.

The storage requirements of these different energy sources for a typical diesel coach weighing 44 tonnes with a 130 cubic metre interior space are visualised in Figure 3b. This considers that the loss of storage space due to the requirement to store hydrogen in cylinders is 20% of the cylinder's volume. The combined weight of hydrogen storage is considered to be 840 kg (750 kg tank plus 90 kg of gas) which compares with 730 kg for a typical fuel tank. To store the same amount of energy, the required battery would double the weight of a typical diesel coach as shown in Figure 3b.

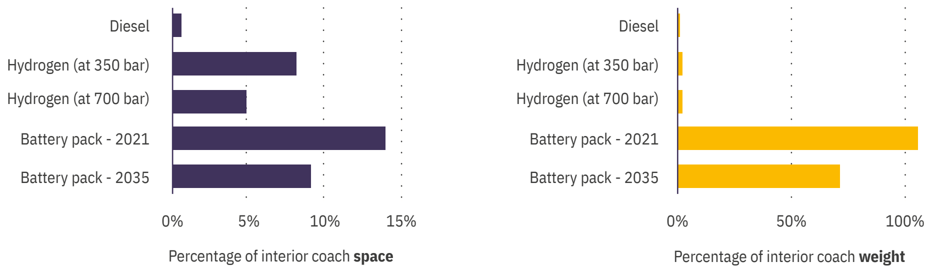


Figure 3b Energy storage space and weight requirements for a typical diesel coach

This illustrates why Network Rail's TDNS assumes that battery trains have a range of 60 to 80 km before they need recharging. There is progress in this area, with one company (Vivarail) developing a fast charge solution that could charge a battery in seven minutes[18]. However, it is often not operationally acceptable to stop a train for this length of time at an intermediate station. *Battery traction is therefore only suitable for short end-to-end journey distances, limiting its use to branch lines or to enable electric trains to travel for short distances off the electrified network.*

It has been proposed that battery trains could operate between nodes of electrification. Such proposals do not take account of the need to operate freight trains or the cost of power supplies to individual nodes whose cost would be comparable with full electrification.

Battery and hydrogen traction can provide acceleration comparable with electric trains. Battery trains have 81% of the energy efficiency of electric trains[19]. As shown in Appendix 3, hydrogen trains have only about 34% of the efficiency of electric trains.

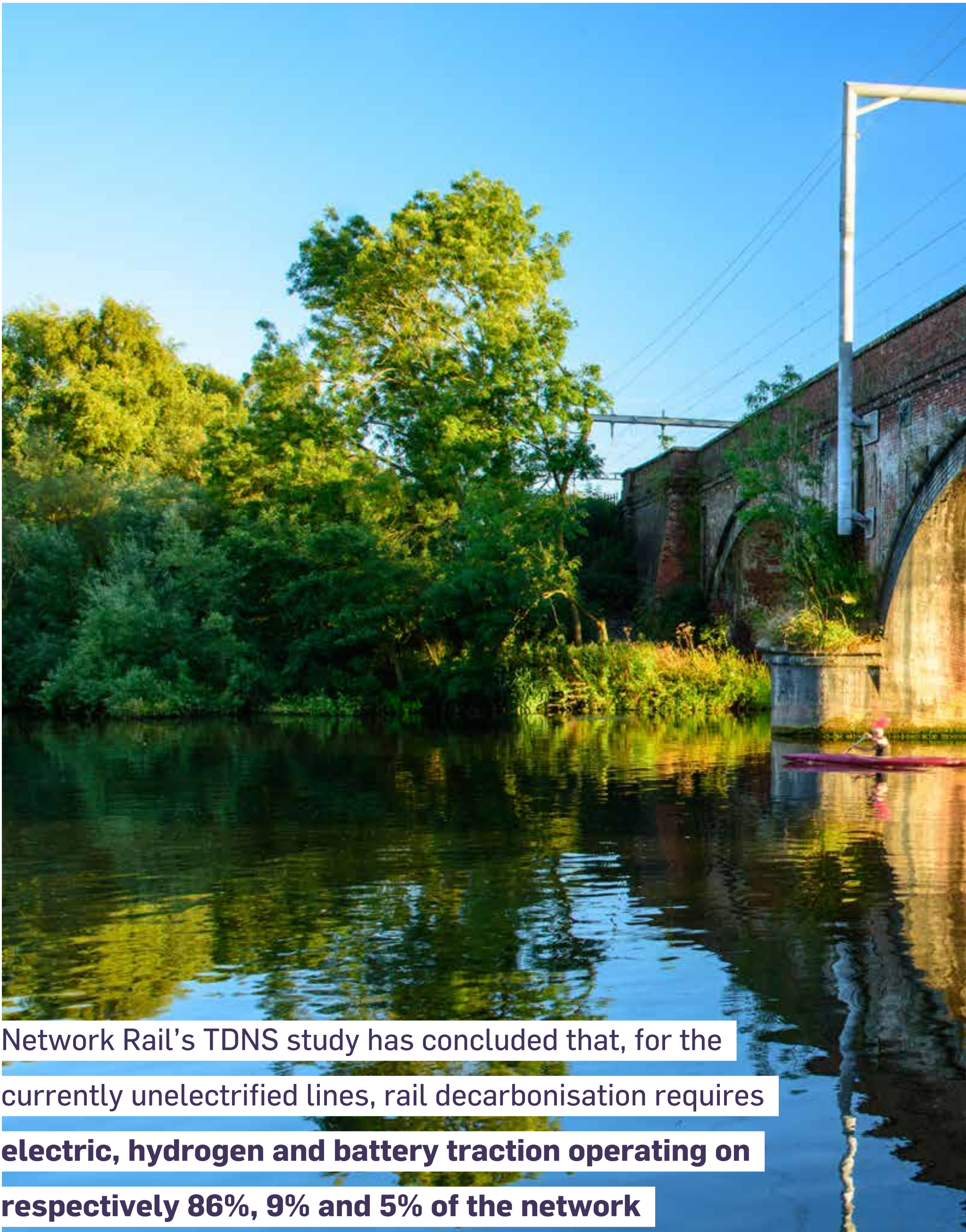
there is not sufficient space to fit traction batteries or store hydrogen within a freight locomotive

As for electric trains, battery and hydrogen trains have regenerative breaking and so can recover energy when braking or going down gradients to charge their traction batteries.

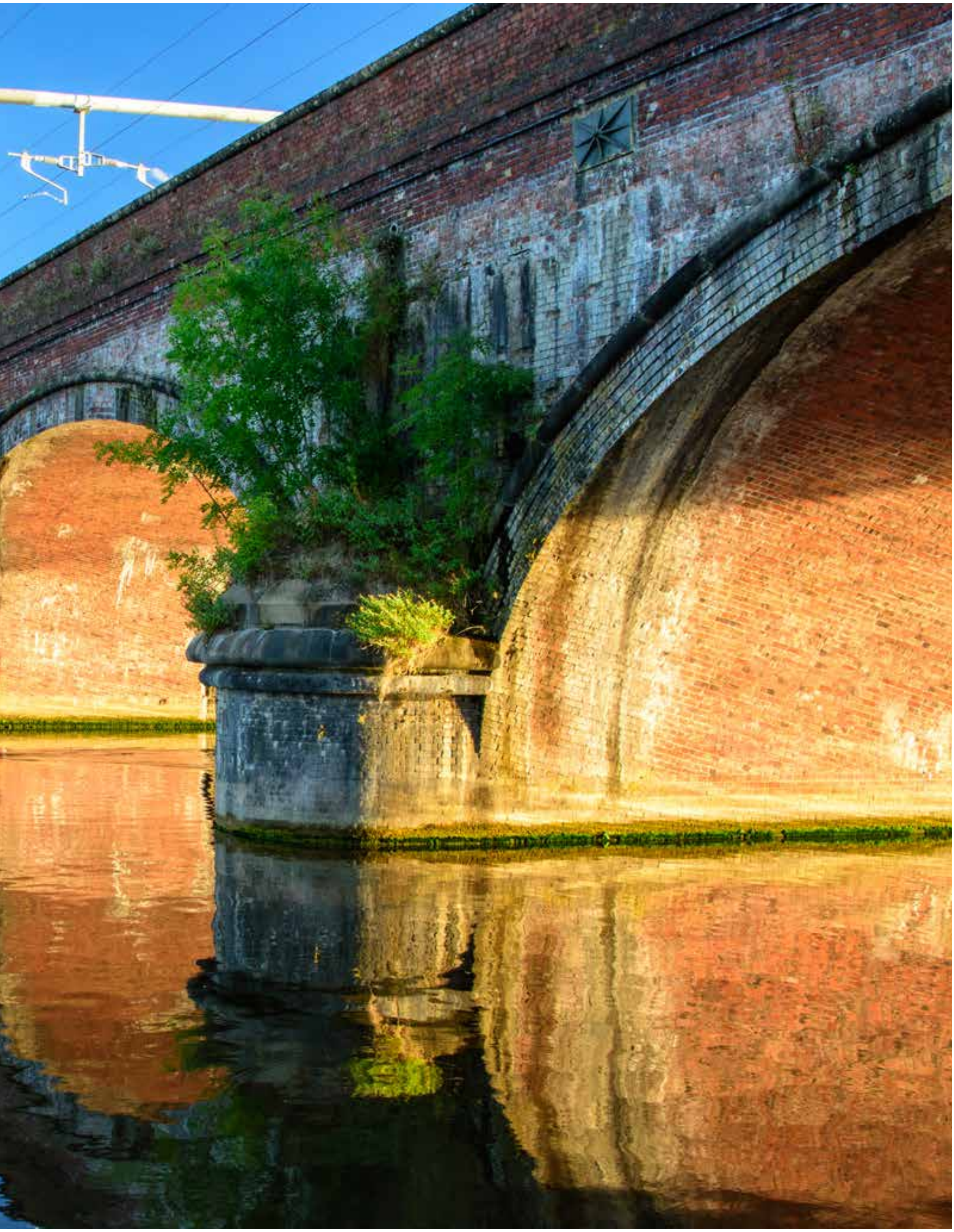
Hydrogen rail traction has been made possible by recent developments in fuel cell technology. The hydrogen passenger trains now in service in Germany and Austria show this technology has been proven in an operational environment. These operate passenger trains up to 160 km/hr with a range of about 1000 kilometres and carrying their fuel on the train roof. However, due to hydrogen's low energy density and the constrained British loading gauge, the proposal to convert surplus trains into hydrogen trains requires them to store hydrogen inside the train (unlike in Europe) which reduces the passenger space. It is possible that this might not be a problem with a new build. However, a new design would require a large production run. This limited energy storage also limits a hydrogen train's maximum speed and reduces its range, particularly on a route with frequent stops.

Hydrogen does not exist in its natural state and so must be produced before it can be used. This can be done by an electrolyser plant at a strategically located depot. Such a plant requires only sufficient land and a suitable electricity and water supply. Its capital cost would be of the order to £1 million per train.

Appendix 3 describes hydrogen trains and hydrogen depot plant in more detail.



Network Rail's TDNS study has concluded that, for the currently unelectrified lines, rail decarbonisation requires **electric, hydrogen and battery traction operating on respectively 86%, 9% and 5% of the network**



3.5 **Comparing battery / hydrogen and diesel traction**

Although diesel traction has a poor performance and efficiency compared with electric traction, it can provide sufficient power to operate intensive fast passenger services and heavy freight trains and sufficient fuel for long distances within tanks of a practicable size.

As a result of the energy storage limitations of battery and hydrogen traction, they cannot be used on freight trains or replace diesels on long-distance and intensive passenger services. Battery and hydrogen traction can, however, offer good passenger train performance for short and medium distances.

For these reasons, Network Rail's TDNS study has concluded that, for the currently unelectrified lines, rail decarbonisation requires electric, hydrogen and battery traction operating on respectively 86%, 9% and 5% of the network.

3.6 **Biofuels**

Biofuels are potentially net-zero carbon fuels that can be burnt in existing diesel engines. However, the production of such fuels can have large indirect land-use emissions. This is particularly true for vegetable-oil based biofuels[20]. There are also concerns that increased demand for crop-based biofuels could result in food shortages and higher food prices if they are grown on land previously used to grow crops.

The CCC considers that biofuels can play a significant role in meeting long-term climate targets. However, to do so they must be produced as part of a system of sustainable land use which limits their production. The CCC's mid-range 2050 scenario for the production of such fuels is 90 TWh per annum which is equivalent of 8 million tonnes of oil or 14% of the petroleum used for transport in Britain.

Hence biofuels are a finite resource which must be prioritised for the most valuable end-uses such as aviation for which there are currently no alternative low-carbon options. CCC therefore considers that the use of biofuels in surface transport should be phased out during the 2030s[21].

Any trains that used biofuels instead of diesel would be less efficient, less powerful, and more expensive to operate for the reasons explained in section 3.1.

For the above reasons, the contribution of biofuels to rail decarbonisation will at best be limited to a small transitional or residual role.

3.7 **Freight locomotives**

The diesel tank on a class 66 freight locomotive stores 6,400 litres of diesel fuel[22] and occupies 6.4 cubic metres. The data in Figure 3a shows that storage of the same amount of energy would require hydrogen storage of 79m³. Alternatively, this would require 136m³ or 350 tonnes of batteries.

Twice this amount of storage would be required for an alternative self-powered locomotive that offers electric traction performance. Thus, there is not sufficient space to fit traction batteries or store hydrogen within a freight locomotive.

On routes that are not electrified, some diesel locomotives will be required for freight and engineering trains. As this would be quite a small percentage of UK traction energy use, it should be possible for the UK's train fleet to achieve net-zero carbon rail traction by offsetting measures or the use of zero-carbon biofuels.

Diesel/electric bi-mode freight locomotives have a useful role for 'last-mile' operations. However, such locomotives have a limited space for a diesel engine and its cooler group and so, in diesel mode, have typically half the power of a diesel freight locomotive. This low power significantly limits the weight of a freight train that a bi-mode freight locomotive could haul on unelectrified lines. Hence, off electrified lines, bi-mode freight locomotives are only suitable for use on freight-only lines and in freight terminals and the availability of such locomotives does not change the amount of electrification required.

As shown in Appendix 3, the class 70 is Britain's most powerful diesel freight locomotive and delivers 2,500 kW at the rail. Whilst this is sufficient to haul freight trains, when climbing steep gradients (especially between Lancaster and Glasgow) or accelerating to line speed, such trains have limited performance which reduces line capacity and can delay passenger trains.

A class 92 electric locomotive has twice the power of a class 70 diesel. *Expanding the electrified network to make greater use of such electric trains would promote freight modal shift from the resultant faster freight trains and reduced delays to passenger trains.* A reduced speed differential between passenger and freight trains would increase passenger capacity on the mixed traffic railway and so also facilitate passenger modal shift.

A significant increase in electric freight haulage does not require a large-scale electrification programme. A study by the Chartered Institute of Logistics and Transport's Rail Freight Forum[23] has concluded that just 500 route miles of electrification would enable about 70% of UK rail freight to be electrically hauled, as Figure 4 shows overleaf.

Figure 4 CILT rail freight forum Electrification for Freight study showing how 500 miles of electrification would enable 66-75% of rail freight to be electrically hauled.

East West Railway is currently being built as an unelectrified railway

RAIL DECARBONISATION — TRANSITIONAL SOLUTIONS

4

recent electrification programmes have been delivered to cost and budget

As large-scale electrification is a long-term programme, there is a requirement for transitional decarbonisation arrangements, some of which are shown below. These transitional arrangements will allow carbon savings to be made immediately and accumulate over time.

4.1 Battery and hydrogen trains

Many passenger diesel multiple units will need to be replaced well before completion of the large-scale electrification programme. Thus, prior to then, there will be a requirement for more battery and hydrogen trains than those needed when the electrification programme is completed. Early deployment of these battery and hydrogen trains as an interim solution would deliver earlier carbon reduction.

Early deployment of battery and hydrogen trains provide a useful transition technology

It is important to gain fleet operational experience of hydrogen trains before large numbers are ordered, as many diesel trains will soon be life expired. The proposal to operate a fleet of hydrogen trains from the Tees hydrogen hub would provide this experience and give confidence that hydrogen traction is a viable technology. If authorised in 2021, this fleet could be in service in 2024.

Batteries fitted to electric trains provide a useful transitional technology, as they can enable them to operate 'off the wire' and have their batteries charged whilst under the wire. This supports decarbonisation as it is possible to remove diesel trains before route electrification is completed. However, such battery/electric bi-mode trains are sub-optimal as, for most of their route, they are heavier than they need to be.

Furthermore, battery trains are less efficient than electric trains. Therefore, they should be designed to be easily converted to electric-only operation once a route is fully electrified. Modern traction electronics facilitates this, but train specifications should emphasise the need for easy removal of the batteries.

4.2 Diesel / electric bi-mode trains

Bi-mode units that can run under their own diesel power and on electrified routes offer immediate carbon savings, but only if used to replace diesel running on electrified routes, or as part of a staged transition during electrification of a route. For example, Class 800/1 units on the 435-mile London to Inverness route only use diesel power for their last 145 miles to Inverness. As a result, they have about a third of the carbon emissions of the Inter City 125 trains they replaced, which were diesel powered all the way from London to Inverness[24].

However, when operating in diesel mode, they only have 70% of their electric mode power (Figure 11, Appendix 3). Furthermore, each nine-coach unit has five engines, weighing seven tonnes each. This is 8% of the weight of the train and incurs a significant carbon cost over the train's lifetime.

Although their traction flexibility can help with the transition to an electric network via a rolling programme of electrification, their diesel engines means that they cannot ultimately be part of a zero-carbon railway. When specifying these trains, similar consideration should be given to future conversion to electric-only as with battery trains.

4.3 **Hybrids and dual fuel**

Existing diesel units can be made more efficient by conversion to hybrid operation which can also eliminate harmful diesel emissions at stations. A class 165 for use on Chiltern Railways is being modified in this way. This involves the removal of old batteries, engine and transmission and their replacement with an underfloor 300kW traction motor, traction battery packs and twin 120kW generator sets. This is expected to offer a 25 per cent reduction in carbon emissions as it operates like a hybrid car – with one additional advantage. This is that GPS control will ensure that the unit operates in battery-only mode in stations and other sensitive areas, such a low-emission zones.

Another useful transitional technology is modifying diesel trains to run on a combination of diesel or liquified natural gas (LNG), with the LNG stored at minus 162 degrees centigrade. This offers carbon emission reductions of about 35%. This is to be trialled on a Grand Central Class 180 DMU and is projected to give 20% fuel savings with a three to five-year payback.

Although they offer a financial payback, widescale modification of existing fleets to hybrid or dual fuel operation presents significant challenges and high initial costs which may require strategic direction and appropriate incentives.

RESEARCH AND INNOVATION

5

Electrification saves lifetime costs of around £2 to £3 million per passenger vehicle

5.1 **Future-proofed electrification**

Whilst research and innovation can contribute much to rail decarbonisation, it is important to understand their limitations. Research cannot, for example, change the laws of nature or the physical properties of materials.

Section 3.1 explains why electric trains are more efficient, more powerful, and cheaper to operate than diesel traction, while section 3.4 and Appendix 3 show that electric traction has significant advantages over hydrogen and battery traction. This explains why Network Rail's TDNS study concluded that, if diesels are to be abolished, battery and hydrogen traction are only suitable for 14% of the currently unelectrified rail network.

As shown in Figure 3a, the Advanced Propulsion Centre predicts that battery capacity might be almost doubled by 2035. If so, this might make battery traction a viable alternative to hydrogen. However, whilst this might change the mix of battery and hydrogen traction, it would have a minimal effect on the scale of the required electrification programme.

Electric trains are a future-proofed technology that is unique in offering potentially net-zero carbon high-powered transport because:

- **The electricity they receive can be generated from any power source.**
- **Their power is limited only by the amount of energy they can collect from overhead line or third rail – in contrast self-powered traction is limited by the on-board power plant or battery size.**
- **They use electricity as it is needed and so do not have to store energy on board.**
- **The second law of thermodynamics states that whenever energy is converted from one state to another (e.g. heat to motion) useful energy is lost. Unlike other types of rail traction, this is not a problem for electric trains which collect electrical energy and feed into their electric motors without any energy conversion process.**

No amount of research can change any of the above.

5.2 **Hydrogen trains**

The fundamental constraint of hydrogen trains is the unchangeable physical property of hydrogen's low energy-density. Hence, a large volume is required to store hydrogen's energy. On trains, hydrogen is currently stored as a compressed gas at high pressure (350 bar). Compressing hydrogen in this way requires 6% of its energy[25]. Alternative storage could be:

- **COMPRESSION AT 700 BAR –** Hydrogen powered cars store the gas at this pressure to give them an acceptable range. However, this requires a disproportionate amount of energy to compress the gas as compressing hydrogen to 700 bar only stores 60% more gas than 350 bar. Furthermore, it needs more expensive tanks and requires fuelling stations to store hydrogen at a pressure greater than 700 bar.
- It may be possible to develop suitably shaped tanks for compressed hydrogen so that they can be more effectively packaged on a train to take up less storage space.
- **AS A LIQUID –** In liquid form hydrogen has an energy density of 8 MJ/litre which is almost three times that of hydrogen compressed at 350 bar. However, at atmospheric pressure, liquid hydrogen has to be stored in cryogenic tanks at minus 253 degrees centigrade (20 degrees above absolute zero). Hydrogen liquefaction requires 30% of its energy[26]. Storage of hydrogen in this way presents significant technical challenges. The only vehicles that use liquid hydrogen are space rockets. It is being considered as a possible net-zero carbon alternative for aviation.

- **METAL HYDRIDES** – these can absorb hydrogen to store it at a low pressure (20 bar) in a vessel one fifth the size of a 350 bar compressed hydrogen tank. However the hydride's absorption of hydrogen is a slow process which generates a great deal of heat. Separating the hydrogen from the hydride requires heat to reverse this process with temperatures up to 500 degrees centigrade. The total energy for heating and compression is about 15 MJ/kg which, as Figure 3a shows, is 23% of the energy of the hydrogen. Despite offering much reduced storage space, hydrides are unlikely to be a practicable method of storage for hydrogen trains due to the challenges of managing and supplying heat for this process and refuelling times that are of the order of an hour or two[27].
- **AMMONIA** – a compound of nitrogen and hydrogen which can be stored as a liquid at atmospheric pressure at minus 34 degrees centigrade or under a pressure of 10 bar at ambient temperatures. It has an energy density of 12.7 MJ/litre which is over four times that of hydrogen stored at 350 bar. Ammonia is considered to be a potential net-zero carbon solution for ships that have large machinery spaces, especially if it could fuel existing diesel engines. However, on trains, it presents a significant health hazard[28].

The decision to store hydrogen, compressed at 350 bar on Alstom's iLint train, was the result of development work over a number of years to determine the best trade-off between cost, practicability, efficiency, and storage volumes. It is possible that emerging research might reduce the space needed for hydrogen storage. However, there are no known storage methods that could significantly increase the energy density of stored hydrogen to a value that is remotely comparable with diesel fuel.

Moreover, as hydrogen traction requires two energy conversion processes (electricity to hydrogen and vice versa), plus the energy needed to compress hydrogen (Figure 16, Appendix 3), it is unlikely that the overall efficiency can ever be significantly increased.

5.3 **Batteries**

The UK's Advanced Propulsion Centre provides funding and support to help the automotive industry transition to net-zero carbon emissions. Figure 5 is its roadmap for battery development which provides a credible indication of how battery capabilities might develop. It indicates that by 2035 the volumetric energy density of batteries, and therefore the range of battery trains, could be significantly increased and battery costs might be halved.

		2020	2025	2030	2035
Pack Indicators	**Transient Discharge Power Density (W/kg)**	715	825	945	1070
	Charge Acceptance (Continuous C Rate)	1.5	2.5	3.5	4
	Gravimetric Pack Energy Density (Wh/kg)	185	210	240	275
	Volumetric Pack Energy Density (Wh/l)	470	540	640	720
	Pack Cost ($/kWh)	125	97	77	63

Figure 5 Battery pack capabilities as predicted by the Advanced Propulsion Centre

This predicted enhancement in battery capability by 2035 might give battery trains a range comparable with hydrogen and so could change the predicted mix of battery and that of hydrogen trains. However the capabilities of such self-powered trains would still be much less than those of electric trains. *Hence such an improvement in battery range is unlikely to significantly change the conclusions of the TDNS report in respect of the need for an extensive electrification programme.*

5.4 **Transitional solutions**

Further research is required into technologies that can be used to modify existing trains to reduce emissions from diesel traction. Two such examples are diesel/electric bi-modes (4.2) and hybrids and dual-fuel (4.3).

5.5 **Efficient electrification**

There is significant potential for innovations to reduce the cost of electrification, and these are actively being progressed by the industry and academia. Every aspect of the system architecture, design and construction processes has been appraised to identify areas for improvement. The need for costly bridge reconstructions is being reduced by surge arrestors and insulation methods to reduce the clearance required. Several additional workstreams are under way in this regard, and the outputs of these will be available to feed into all future electrification schemes. The examples below potentially further reduce the requirement for bridge reconstructions:

- **Reduction of wire uplift allowances at bridges;**
- **Introduction of insulating pantograph horns;**
- **Reassessment of OLE gradient rules;**

Benchmarking piling techniques and OLE structures against European practice could further reduce costs whilst the development of power supply systems using modern protection technology could limit the amount of switchgear needed at substations.

Recently a Static Frequency Converter (STC) feeder station fed from a local 33kV network was commissioned at Doncaster. Network Rail estimates that the use of this SFC technology could reduce the cost of new feeder stations by 60% as they do not require a connection to the high voltage grid and provide the power utility with a balanced supply into the railway power infrastructure[29].

As the Riding Sunbeams project has shown, there is also significant potential for cost savings if solar panels and wind turbines could be connected directly to Network Rail's electrification system. This would require the development of a suitable three-to-single phase converter and a change to Network Rail's licence conditions, allowing it to export surplus electricity from such off-railway generation to the National Grid.

CONCLUSIONS

6

Although bi-mode traction flexibility can help with the transition to an electric network, their diesel engines mean that they cannot ultimately be part of a zero-carbon railway.

6.1 The use of electricity, either by electric trains that use it as it is generated, or by storing it on battery and hydrogen trains, is the only traction option for rail decarbonisation.

6.2 The contribution of biofuels to rail decarbonisation will at best be limited to a small transitional or residual role.

6.3 Electric trains are a unique technology in that they can use electricity as it is generated to offer high-powered net-zero carbon transport. They are the only decarbonisation option for rail freight and for rail passenger services requiring high-speed and high-power for other than short distances. Hence, rail decarbonisation requires a large-scale electrification programme.

6.4 Electric trains are future proofed since research and innovation cannot change the inherent features that give them greater power, range, efficiency and lower operating costs than self-powered traction.

6.5 UK rail's greatest potential contribution to UK decarbonisation is accepting passenger and freight traffic from less carbon friendly modes of transport. Attracting traffic from other modes requires high-powered traction which, for most passenger services and all freight services, requires electrification.

6.6 Cost effective electrification is best delivered as part of a rolling programme. Innovations are also reducing the cost of electrification. This will further improve its already positive business case when delivered at current electrification costs, as shown in Network Rail's TDNS.

6.7 The UK rail decarbonisation strategy must consider how best to incentivise modifications of existing diesel traction to reduce carbon emissions pending electrification.

6.8 The carbon benefits of electrification far outweigh the embodied carbon arising from the provision of an electrified railway.

An example of the high reliability of modern electric trains is the Hitachi-built class 385 electrical multiple units which regularly achieve 50,000 miles between technical incidents


385 104
express

APPENDIX 1

CHALLENGES AND SOLUTIONS FOR UK DECARBONISATION

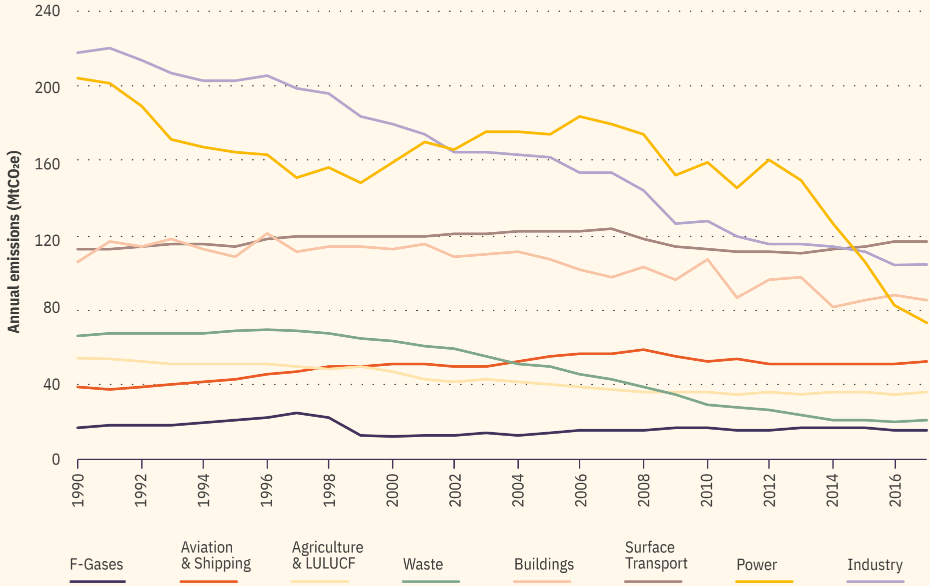


Figure 6 UK CO_2e sector emissions 1990 – 2018 | CCC – Net Zero report

Targets and progress to date

Britain was the first country in the world to set itself a legally binding target to reduce greenhouse gas emissions in the 2008 Climate Change Act. By 2050, this required the UK's greenhouse gas (GHG) emissions to be 80% of those in 1990. Following the publication of the Net Zero report by CCC in 2019, Parliament amended this Act to require that the UK should achieve net-zero emissions by 2050.

Up to 2018, Britain has reduced its emissions to 58%[30] of its 1990 level. Figure 6 shows that most of this reduction was from the power sector with transport now the largest source of GHG emissions (23%). The power sector has reduced its emissions by the increasing use of renewable energy and burning gas instead of coal. Britain's largely-electrified passenger train fleet has been able to take advantage of this greening of electricity generation and so is the only transport mode that is reducing its emissions. Further electrification would reduce rail emissions even further.

Decarbonising transport

UK transport currently consumes 55 million tonnes of petroleum oil. Petrol/diesel fuels store a large amount of energy in a small volume (diesel 36 MJ per litre) and are easily transported and stored. Weaning Britain's transport off petroleum is a significant challenge for all sectors except rail, which already has proven technology to do this in the form of electrification.

The alternative use of biofuels is problematic. The CCC Net Zero report considers that "there is likely to be a finite supply of biomass available to the UK that is truly low-carbon" and that this limited supply of biofuels should be used in sectors where there is no alternative (e.g. aviation).

The only other alternative energy source for transport is electricity. Electricity can be easily "transported" by the distribution network, but only to fixed locations. If vehicles are to be electrically powered, they must store and carry this electrical energy in batteries, which currently can only store 1.7 MJ per litre. As shown in Figure 3a, to store the same amount of energy, a battery pack requires a space 21 times that of a diesel tank. By volume, a battery pack has 5% of the energy in a diesel tank.

The only other known practical way of storing electricity on a train is using it to produce hydrogen by electrolysis which uses electricity to split water into hydrogen and oxygen. Hydrogen fuel cells reverse this process by combining hydrogen with oxygen in the air to produce electricity. Figure 3a shows that the energy stored in a high pressure (350 bar) hydrogen tank is 2.9 MJ per litre. This is 70% more than a battery pack but is still only 8% of the energy in a diesel tank.

UK transport currently consumes 55 million tonnes of petroleum oil

Electric trains, trams and trolley buses do not have to store electrical energy as they are the only form of transport that can use electrical energy as it is generated. As their power is limited only by the amount of current that they can collect on the move, they offer the only high-powered net-zero carbon form of transport.

Future UK electricity and hydrogen requirement

The total amount of energy generated by the UK in 2018 was equivalent to 30 million tonnes of oil which is 55% of the total petroleum energy used by transport[31]. The CCC concluded that if Britain is to achieve net-zero GHG emissions a significant increase in zero-carbon power generation and hydrogen production is required as shown in Figure 7. This is needed not just for transport, but for domestic heating, industrial processes, and other requirements.

Ensuring sufficient net-zero carbon electricity by 2050 requires a large-scale increase in renewable generating capacity together with large scale carbon capture and storage (CCS). This is needed so that, together with nuclear power, gas and biofuels can provide a net-zero carbon supply when the wind does not blow.

Most of the projected hydrogen requirement is for direct heating; however a relatively small amount, produced by electrolysis, will be needed for transport. The CCC consider that most of this hydrogen will be needed for Heavy Goods Vehicles. The government aims to deliver this additional green electricity generation and hydrogen through its ten-point-plan for a green industrial revolution[32]. It aims to add 40GW of offshore wind capacity, provide 5GW of low carbon hydrogen production and capture 10 million tonnes of carbon dioxide each year by 2030. The UK Government's ten point plan for a green industrial revolution commits to green public transport by electrifying more railway lines.

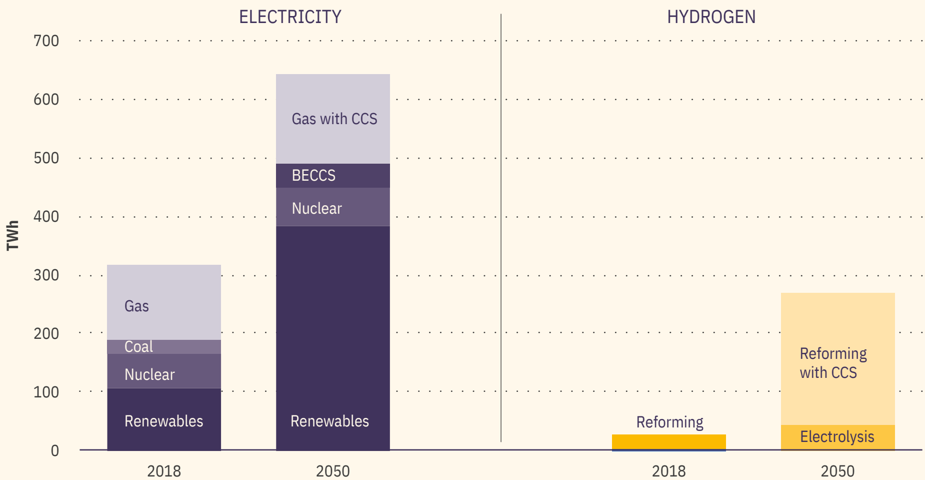


Figure 7 Electricity and hydrogen requirement

Hydrogen for transport: HGVs - 22 TWh, Buses - 3 TWh; Trains 0.3 TWh

APPENDIX 2

MODAL SHIFT OF PASSENGER AND FREIGHT TRAFFIC TO RAIL

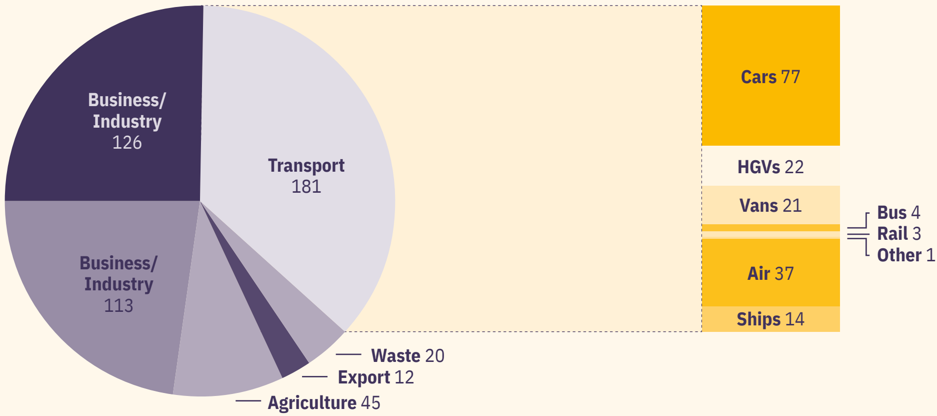


Figure 8 2017 emissions by sector.

Department for Business, Energy & Industrial Strategy

2017 UK GHG emissions – 510 million tonnes CO_2e. Final UK greenhouse gas emissions national statistics 1990-2017. Includes UK fuel for international aviation (35 Mt CO_2e) and shipping (8 Mt CO_2e) which, from 2018, this dataset no longer reports.

In 2017 the UK's total GHG emissions were 510 million tonnes of carbon dioxide equivalent gases of which transport accounted for 181 million tonnes as shown in Figure 8. This also shows that rail's emissions are only three million tonnes. However passenger and freight modal shift to rail from less carbon friendly transport modes offers savings much greater than this.

This is illustrated in Figure 9 which shows that, in 2018 car, bus, and air emissions per passenger kilometre were respectively 2.7, 2.4 and 4.8 times those of rail. It also shows that road freight emissions per tonne kilometre were 9.1 times those of rail freight.

UK DOMESTIC TRANSPORT 2017				WITH MODAL SHIFT TO RAIL			
Passenger				From Road -4%		From Air -20%	
	Billion Pass km	Emissions MtCO_2e	Gram CO_2e/km	Billion Pass km	% Traffic Change	Emissions MtCO_2e	Emissions Savings
Car	707	69.7	99	679	96%	66.9	**2.8**
Cycle	5	0		5	100%	0	**0**
Bus / Coach	38	3.4	89	38	100%	3.4	**0**
Rail	79	2.8	35	109	138%	3.8	**-1.1**
Air	9	1.6	178	7.2	80%	1.3	**0.3**
Total	838	77.5		838		75.4	**2.1**
				Passenger Modal shift saving			**2.1**
Freight				**4 % Modal Shift to Rail**			
	Billion Tonne km	MtCO_2e	Gram CO_2e / Tonne km	Billion Tonne km	% Traffic Change	Emissions MtCO_2e	Change in Emissions
HGV / Van	147	20.7 / 19.5	273	141	96%	38.6	**1.6**
Rail	17	0.5	30	23	135%	0.7	**-0.2**
Total	164	40.7		164		39.3	**1.4**
				Freight Modal shift saving			**1.4**
				TOTAL MODAL SHIFT SAVING			**3.5**

Figure 9 2018 transport emissions showing impact of modal shift[33]

Figure 9 shows that a passenger shift of 4% from cars and 20% from air as well as a 4% freight shift from road to rail would save 3.4 million tonnes of carbon dioxide equivalent gases which is equivalent to all UK rail's current traction emissions.

It also shows that a relatively minor modal shift from road transport would result in 38% more rail passenger traffic. HS2 and capacity enhancements on the existing network are required if rail is to be able to accept such relatively small modal shifts from road and air.

Percentage car passengers traffic	**2%**	**4%**	**6%**	**8%**	**10%**
Increase in rail passenger traffic	17%	34%	50%	67%	84%
Savings – million tonnes CO_2e	1	1.9	2.9	3.9	4.8
Percentage domestic aviation traffic	**10%**	**20%**	**30%**	**40%**	**50%**
Increase in rail passenger kilometres	1%	2%	3%	5%	6%
Savings – million tonnes CO_2e	0.1	0.2	0.4	0.5	0.6
Percentage road freight traffic	**2%**	**4%**	**6%**	**8%**	**10%**
Increase in rail freight tonne - km	17%	35%	52%	69%	86%
Savings – million tonnes CO_2e	0.7	1.4	2.1	2.8	3.6

Figure 10 Scenarios for modal shift to rail

The modal shift scenarios, as shown in Figure 10, have been derived from calculations using the data in Figure 9. These show that it is not unreasonable to consider carbon savings from modal shift to rail of between three and six million tonnes, provided that the rail network has the capacity to accept the extra traffic. If net-zero carbon traction is also achieved, this offers total potential savings of between two- or three-times rail's current emissions.

Modal shift, however, requires sufficiently powerful rail traction to attract additional traffic. For passenger traffic, this requires high speed and high acceleration, and for freight, it requires locomotives with the performance to reduce journey times and minimise delays to passenger traffic.

As described in Appendix 3, if diesel traction is to be abolished, only electric traction can offer the required performance to attract the required modal shift.

a relatively minor modal shift from road transport would result in 38% more rail passenger traffic

Note: The data used in this analysis is pre-Covid. Rail's per passenger km / tonne km emissions record will be particularly poor in 2020 due to much reduced traffic. However this is not considered to be relevant in the long term.

APPENDIX 3

ELECTRIC, DIESEL, HYDROGEN AND BATTERY TRACTION

	ELECTRIC		DIESEL		
	Traction Type	**Power at Rail**	**Traction Type**	**Power at Rail**	**Electric to Diesel Ratio**
Freight loco	Class 92	5,040 kW	Class 66	2,214kW	**228%**
Passenger loco	Class 87	3,700 kW	Class 50	1,560 kW	**237%**
Multiple unit	Class 385	500 kW	Class 170	260 kW	**193%**
High Speed Train – per coach	Class 390	567 kW	IC 125 Class 220	311 kW 480kW	**182%** **118%**
Bi-mode – per coach	Class 801	502 kW	Class 220	335 kW GE 720kW engine	**150%**

Figure 11 Electric and Diesel traction power comparisons

Comparison of electric and diesel traction

For overhead line electrification, the power of an electric train is limited only by the current it can collect from its pantograph. In contrast, the power of a diesel train is limited by its engine(s).

As well as providing power to move the train, there is also the requirement to provide sufficient power for the train's hotel load and auxiliary machines. For an electric train, this is not a problem, as the electrical supply provides sufficient power for traction and all other requirements. However, on a diesel train, the available space and weight restrictions constrain the size and power of the diesel engine. Hence, as shown in Figure 11[34], for comparable types of traction, electric trains are significantly more powerful than diesel trains. In Figure 11, the power of a diesel train at the rail is the power of the engine less a hotel load of 25kW per coach and 10% of the engine power for auxiliary machines and generator/ transmission losses. The power of an electric train at the rail is the power of its electric motors.

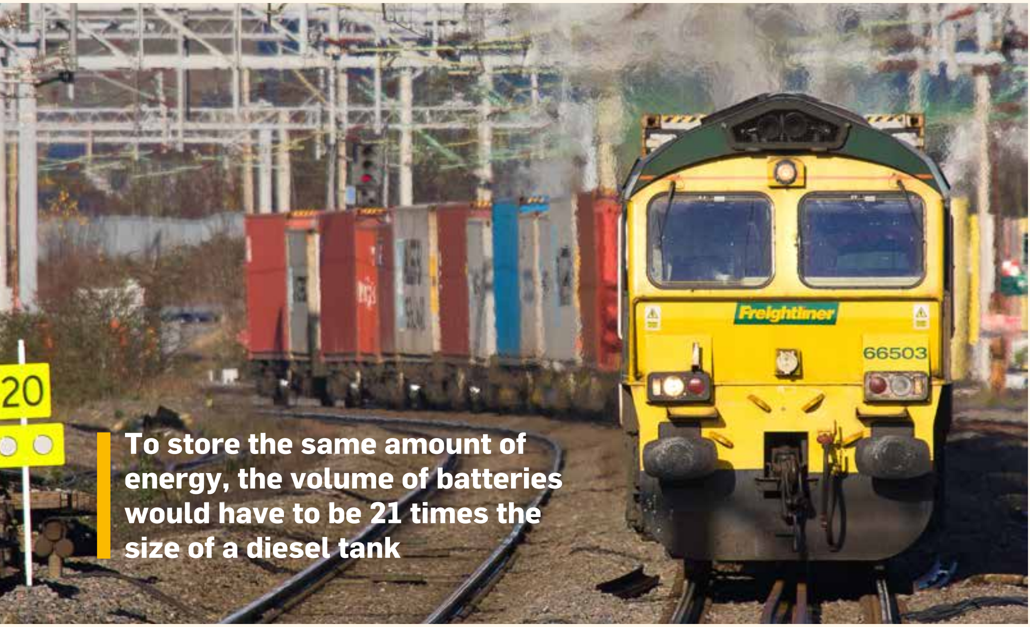
The extra power of electric traction offers significant performance benefits. For example, after electrification of the Edinburgh to Glasgow service, trains were able to accelerate to 60 mph in 50 seconds compared with 1 minute 40 seconds required by diesel trains. This makes it much easier for trains to recover from any delays. The introduction of more powerful electric trains has been shown to attract extra traffic to the railway.

electric traction offers significant performance benefits

The chart in Figure 12 is from Network Rail's 2009 Electrification Route Utilisation Study. Over a 30-year vehicle life, these savings total £2 to £3 million per vehicle at 2020 values assuming an average daily vehicle mileage of between 300 and 500 miles per day.

	DIESEL VEHICLE	ELECTRIC VEHICLE
Maintenance per mile	60p	40p
Fuel per mile	47p	26p
Lease per annum	£110,000	£90,000
Track wear per mile	9.8p	8.5p

Figure 12 Electric and Diesel traction cost



Battery trains

Vivarail produces the only battery trains currently approved for passenger use in the UK. These have two 100 kWh battery packs on each coach operating with 30-40% reserve capacity, giving each coach about 130 kWh of useful energy. Vivarail considers its trains consume 1.7 to 2.2 kWh per kilometre, which gives a battery range of 60 to 80 km[35]. This is the range assumed by the TDNS study.

The company advises that its battery trains can provide a peak power output of 500 kW, which is comparable to a Class 385 electrical multiple unit, as mentioned in Figure 11.

Provided that suitable charging facilities are available, this makes them suitable for short branch line services or to enable electric trains to travel for short distances off the electrified network.

Vivarail is also developing a fast-charging solution, which would require a train to be stopped for seven minutes for each hour of operation. In some circumstances, this could extend the potential for battery trains. This requires a 1,000-amp charging current which requires a bespoke battery cooling arrangement, battery banks at charging stations and third / fourth rail collector shoes.

To store the same amount of energy, the volume of batteries would have to be 21 times the size of a diesel tank (Figure 3a). For this reason, as TDNS concluded, there is limited use for battery trains, although, as shown in section 5 of this paper, they could be a useful transitional technology to a net-zero rail network.

Hydrogen trains

Hydrogen rail traction has been made possible by recent development in fuel cell technology. However, hydrogen trains can only operate as a hydrogen/battery hybrid train in which a sophisticated control system ensures the best use of fuel cell and battery power and charges the battery, both from the fuel cell and the train's braking.

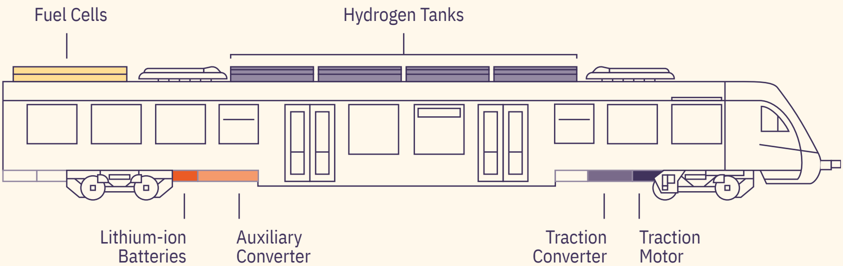


Figure 13 General arrangement of Alstom's iLint hydrogen train

Alstom's Coradia iLint hydrogen train that is in service in Germany has a 200-kW traction battery and 22kW fuel cell on each coach[36]. Hence, when accelerating it has a performance almost equal to that of a Class 385 EMU, as shown in Figure 11.

The significant constraint of hydrogen is its low energy density. As shown in Figure 3a, when compressed to 350 bar (which requires 9% of the hydrogen's energy), it takes up 12 times the space of a diesel fuel tank storing the same amount of energy.

On Alstom’s iLint hydrogen train, the roof-mounted hydrogen tanks give it a range of about 1,000 kilometres. However, Britain's more constrained loading gauge will require the fuel cells to be placed elsewhere within the train.

For this reason, the hydrogen tanks on the 'Breeze' train developed by Alstom and Eversholt Rail are inside the train. The Breeze is the conversion of a redundant three-coach electrical multiple unit into a UK hydrogen train using iLint technology, in which the hydrogen tanks take up a third of each of the two driving coaches.

Figure 14 – The hydrogen 'Breeze' train developed by Alstom and Evershold Rail

Other similar hydrogen trains are being developed in the UK, such as HydroFlex developed by Birmingham Centre for Railway Research and Education and Porterbrook.

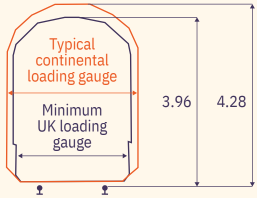


Figure 15 Comparison of UK and continental loading gauge

Although it is the most common element in the universe, hydrogen does not exist in its natural state and must be produced either from methane gas or by electrolysis. Electrolysis is most likely to be the best way of producing hydrogen for trains, as it can produce hydrogen on a small scale, requires only land and an electricity and water supply and is potentially a zero carbon process.

When hydrogen trains use hydrogen produced in this way, they are, in effect, storing electrical energy. As shown in Figure 16[37], the overall process has an efficiency of around 34% and requires 2.9 kW of electrical power to deliver 1 kW to the wheel. However, it is possible to produce hydrogen using surplus overnight wind power to take advantage of low-cost electricity and provide grid balancing for variable renewable power.

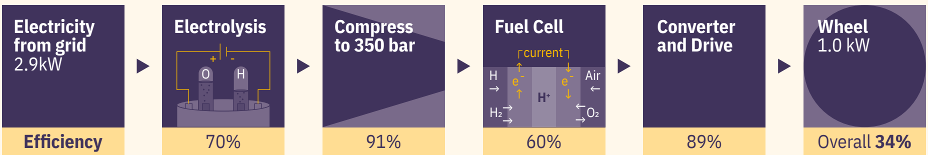


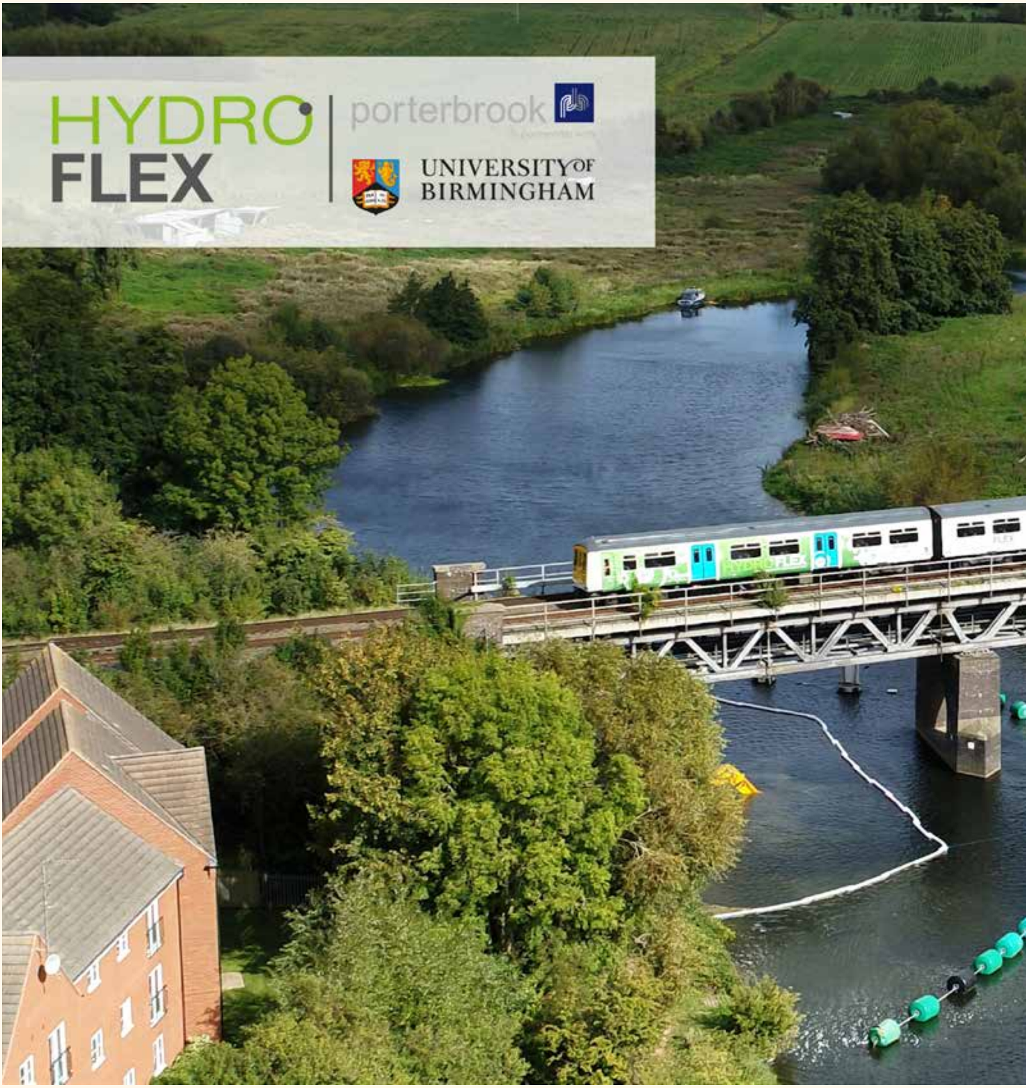
Figure 16 Typical overall efficiency of hydrogen trains

Electrolysis is a mature technology that enables sufficient hydrogen to be produced at strategically located depots without the need for hydrogen pipelines. All that is needed is sufficient land and a reasonable electricity and water supply.

The electrolysis and fuelling hydrogen plant for a trial of ten hydrogen buses in Aberdeen required a 1MW electricity supply and cost about £1.5 million. The trial considered this to be a mature technology that can easily be scaled up[38].

Figure 17 Hydrogen plant for Aberdeen hydrogen bus trial

A typical depot fleet of ten hydrogen trains for rural service would require around 2,500 kg of hydrogen per day (**ref for reference section: RSSB Report; Intelligent Power Solutions to Decarbonise Rail"). The Aberdeen plant was designed to supply 250 kg per day. Hence such a depot plant would cost around £10 million or £1 million per train. If a suitable site was available nearby it might be possible to install a dedicated wind turbine to reduce the cost of electricity, as explained in section 5.5.



↑ **HydroFLEX train** developed by Birmingham Centre for Railway Research and Education and Porterbrook

→ **Vivarail's class 230 unit.** Number 230 002 is a prototype unit which was the first diesel / battery hybrid train authorised for UK mainline operation. Three such units were authorised for passenger operation in 2020.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APPENDIX 4

INTERNATIONAL RAIL COMPARISONS OF ENERGY USE AND GHG EMISSIONS[39]

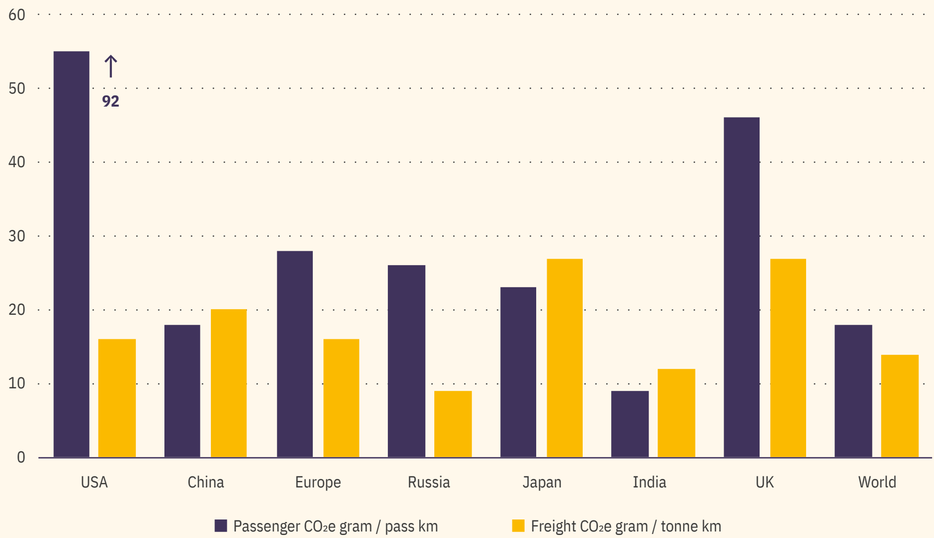

Figure 18 Rail CO_2e emissions (2015)

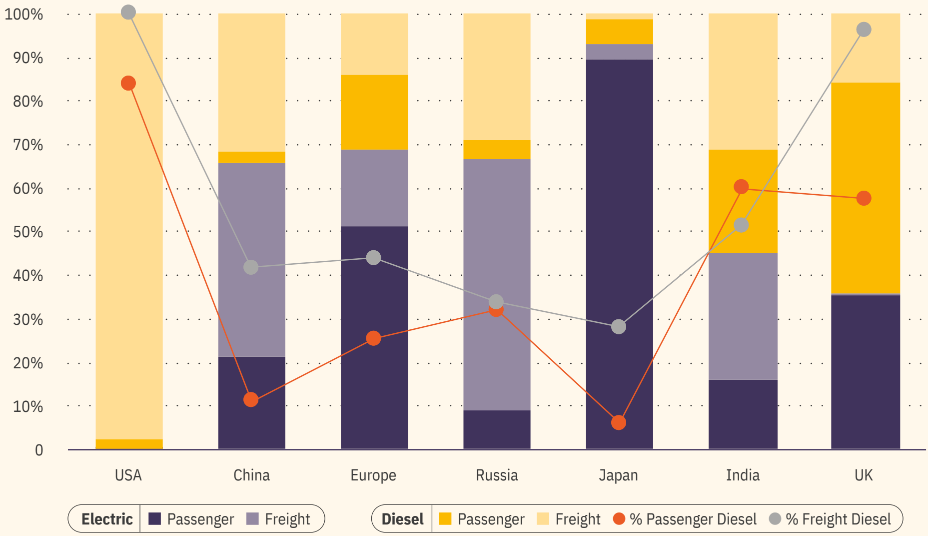

Figure 19 % rail traction energy use (2016)

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2 https://publications.parliament.uk/pa/cm5801/cmselect/cmtrans/876/87602.htm

3 RSSB report T1145 shows that the respective energy efficiency of electric and diesel traction (from original energy source to power at the wheels) is 80% for overhead line electrification and 25% for diesel traction.

4 Figure 1.3 “Net Zero The UK’s contribution to stopping global warming” Committee on Climate Change May 2019

5 Modern Railways, January 2021 “Talkin’ ‘bout re-generation” states that Govia Thameslink Railway’s trains recover 22% of the electricity that they consume.

6 Calculated from total emissions Figure 1.4 Net Zero The UK’s contribution to stopping global warming and UK electricity supplied from Department for Business Energy and Industrial Strategy’s Historical electricity data.

7 Sources RDG Long Term Passenger Rolling Stock Strategy and ORR data table 6105

8 Typical rate of acceleration is 0.65m/s2 for DMU, 1.0m/s2 for EMU. "Study on Further Electrification of Britain’s Railway Network"; 2007; RSSB/Atkins; Appendix D

9 "Traction Decarbonisation Network Strategy - Interim Business Case"; Network Rail; July 2020; section 5.5.31

10 UK diesel vehicle capex is on average 12% higher than for electric vehicles. "Rail Value for Money Study – Rolling Stock Whole Life Costs – Final Report"; 2011; Arup; figs 2.10 and 2.11.

11 For instance on the UK’s West Coast franchise, diesel fuel accounts for 40% of total traction cost, despite only 15% of the fleet being diesel. "Electrification Benefits", Shirres; October 2017; Rail Engineer

12 DMU maintenance costs across Europe are typically 40% higher than for an EMU. "European Benchmarking of the Costs, Performance and Revenues of GB TOCs – Final Report"; 2012; Civity; p65

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WHY RAIL ELECTRIFICATION?

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