Electrification paper

Introduction to the Rail Cluster Project

The Rail Cluster Builder project was awarded to Scottish Engineering in August 2020 and is an 18-month programme funded by Scottish Enterprise and supported by Transport Scotland. The purpose of the project is to facilitate connections for SMEs in the engineering and manufacturing sectors in Scotland seeking to diversify into the rail market.

The project is jointly funded by Scottish Enterprise and the 2014 – 2020 European Structural and Investment Fund through SPRITE (Scottish Programme for Research, Innovation and Technology Ecosystem). This is a small programme which aims to improve the innovation performance of Scotland's Small and Medium Sized Enterprises (SMEs) and stimulate greater coordination between stakeholders and partner organisations to help businesses capitalise on new economic and public sector innovation opportunities.

The roots of the rail cluster project lie in the Rail Services Decarbonisation Plan in which the Scottish Government aims to decarbonise passenger rail services in Scotland by 2035, ahead of the UK's target of 2040. By moving away from diesel and using green sources such as electricity, battery or hydrogen, opportunities will arise for innovation in train manufacturing as well as wider supply chains, supporting the creation of skilled, sustainable employment in Scotland. The Rail Cluster Builder will be key in helping to develop Scotland as a leader in the innovation and manufacture of net zero rail products and services.

The UK government set out in June 2019 its legal commitment to achieve 'net zero' greenhouse gas emissions by 2050. In respect of the railway, in 2018 the DfT challenged the rail industry to remove all diesel-only trains from the network by 2040. The Scottish Government has set a target to decarbonise domestic passenger rail services by 2035.

Purpose of this report

There are a range of technical and academic resources freely available online which explore the primary role of electrification and alternative and interim traction solutions in replacing diesel, and thereby enabling the net zero emission targets set by both the Scottish and UK Governments to be met. This report reviews the publicly available literature and seeks to extract and summarise the most salient themes to provide technical insight for the rail cluster SME community with a particular focus on electrification in Scotland. The aim of this report is to raise awareness, generate discussion and potentially spark new ideas or innovations to support the Rail Decarbonisation Action Plan.

Rail Decarbonisation Action Plan

"Scotland's railway is a success story, with around 76% of passenger and 45% of freight journeys already on electric traction.

We must build on this success by converting more passenger and freight journeys to this environmentally sustainable mode, a key element of our new National Transport Strategy.

Through investment in electrification and complementary traction systems we will decarbonise the traction element of domestic daytime passenger rail journeys in Scotland. It also demonstrates our approach to investment in green technologies and our commitment to creating a greener, more environmentally just economy with growth in greener, more sustainable sectors.

Electrification has many benefits ranging from faster journey times for passengers and freight, improving connectivity between our cities, and creating additional capacity, to lowering industry operating costs, helping to meet our environmental targets, and improving air quality.

All of these benefits will support modal shift from private vehicles and heavy goods vehicles to rail increasing the operational, societal, environmental, and economic benefits. Our vision is for Scotland to have the best air quality in Europe with our transport system contributing to make this happen".

Michael Matheson MSP, Cabinet Secretary for Transport, Infrastructure and Connectivity
Rail Decarbonisation Action Plan July 2020

Climate change

Despite the Covid pandemic and the far-reaching impact it has had on everyone this year, there remains an important focus on climate change and the challenges associated with it.

Did you know that:

- All 10 of the UK's warmest years since 1910 have occurred since 2002?
- The UK was 0.8° Celsius warmer in 2008 – 2017 compared to 1961 – 1990?
- The UK was 20% wetter in 2008 – 2017 compared to 1961 – 1990?
- UK sea level has risen by 16cm?[1]

The rise of more extreme weather conditions has presented many challenges for the rail sector with flooding, landslides and strong winds causing havoc with the rail infrastructure. This highlights further the need for the rail sector to invest in new technologies and infrastructure solutions that can adapt to climate change and provide a more resilient rail network, but also to focus on reducing greenhouse gas emissions.

Rail is already a low carbon contributor in comparison to other transport options as shown in the diagram below from the Rail Decarbonisation Action Plan.

[1] Traction Decarbonisation Network Strategy, Network Rail

Between 2012 and 2018, UK emissions per passenger kilometre fell by 24% for rail compared to 8% for petrol cars, 4% for diesel cars and 10% by buses. [2]

37% of Scotland’s greenhouse gas emissions are from transport (2017)

40% 12.5% 12.5%

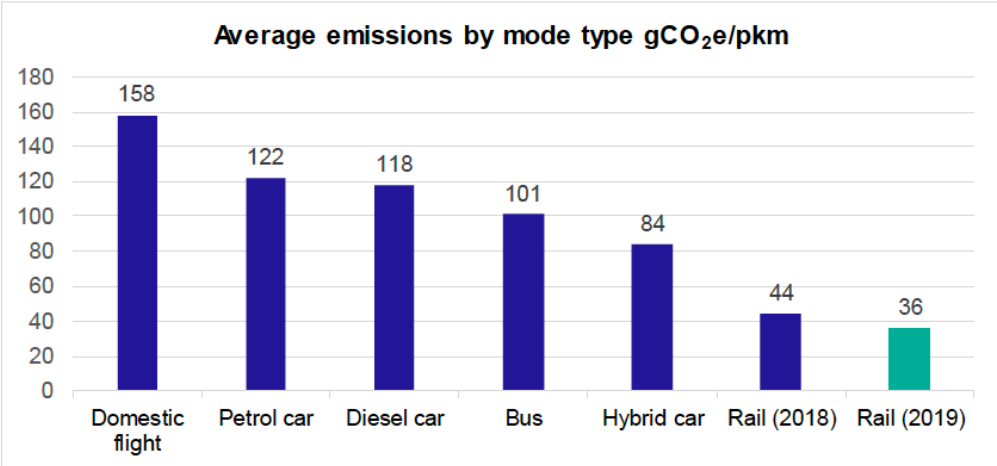
15% 15% 3.2%

1.2% Other 0.6%

[3]

The graph below shows the average emissions by transport mode per passenger kilometre.

You can see Rail is one of the lowest rates of emissions shown in green.



Average emissions by mode type (blue 2018, green 2019)

[4]

Within the rail industry, around two thirds of the direct greenhouse gas emissions are attributable to traction energy, with the remaining third linked to operating the rail network and station and depot operations.

In terms of traction power, the UK rail network can be categorised into four areas shown on the map on the next page: -

• unelectrified – diesel operations

[2] Rail Decarbonisation Action Plan, Transport Scotland, July 2020
[3] Rail Decarbonisation Action Plan, Transport Scotland, July 2020
[4] Rail Decarbonisation Action Plan, Transport Scotland, July 2020

• electrified with 25,000V AC overhead line equipment

• electrified with 1,500V DC overhead line equipment

• electrified with 650V/750V DC third rail (England)

5

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5 Rail Decarbonisation Action Plan, July 2020

Railway electrification in Scotland, 2020

Map showing railway electrification in Scotland, 2020

Electrification in Scotland 2020
- Electrified network
- Non-electrified network

6

Electrified routes across the rail network

Over 6,000 route kilometres of UK railway are currently electrified with electrified routes accounting for 38% of all railway in the UK. Today, around 40.7% [7]of the Scottish rail network is electrified with 76% of all passenger journeys being electrified. The diagram below shows the Scottish network and the extent of electrified lines with work completed between 2010 and 2019 shown in blue.

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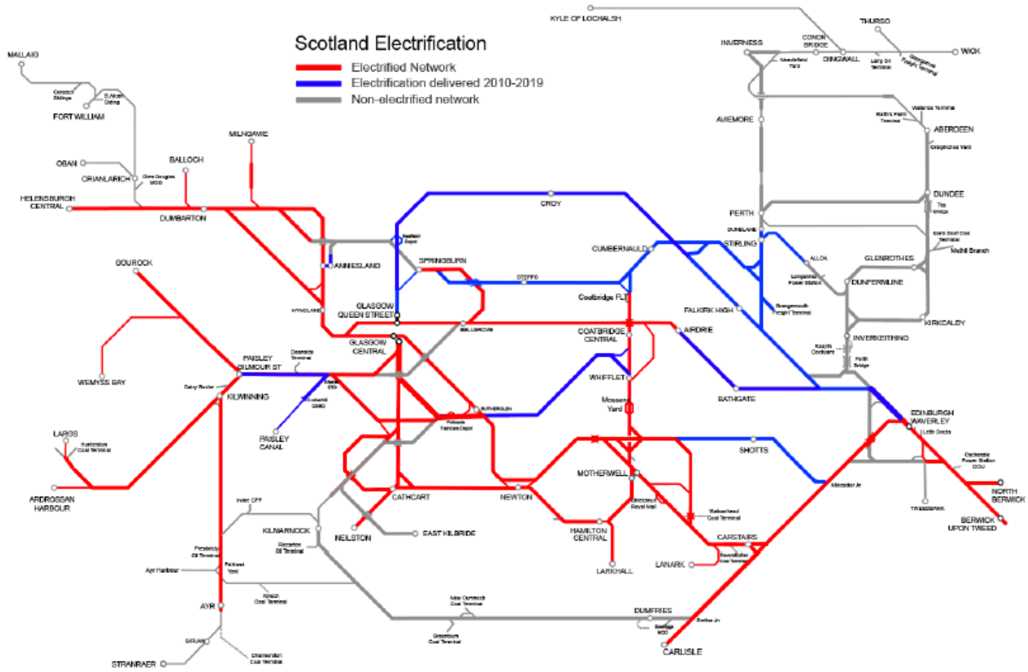
[6] Rail Decarbonisation Action Plan, July 2020

[7] 40.7% single track rail kilometres are electrified, however the Scottish Government uses a different measurement, total track length of the Scottish rail network. Around 29% of the total track length on the Scottish rail network is electrified.

The diagram below shows the extent of electrification work completed between 2010 and 2019.



Map showing extent of electrification work completed between 2010 and 2019
[8]

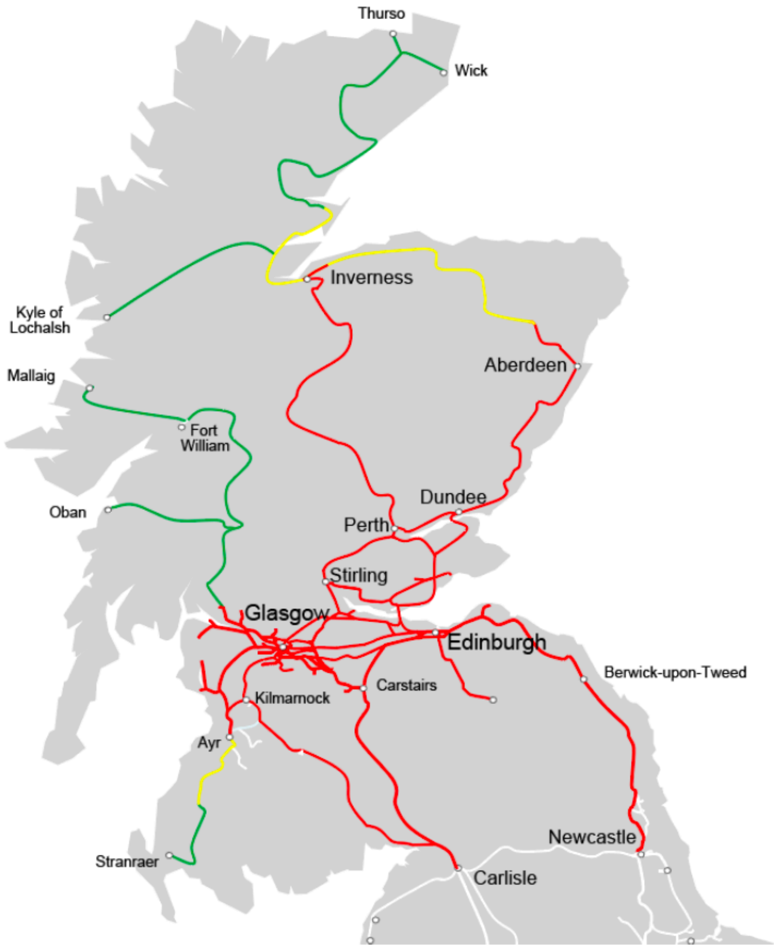
The lines electrified in the last ten year period include:

- the new Airdrie to Bathgate route
- lines of route from Glasgow Central to Paisley Gilmour St
- the Paisley Canal line
- the Cumbernauld line
- the Whifflet route between Rutherglen and Coatbridge
- the Stirling-Dunblane-Alloa route
- the main Edinburgh to Glasgow route via Falkirk High
- the Edinburgh to Glasgow line via Shotts.

[8] Rail Decarbonisation Action Plan, July 2020

Scotland's aims for electrification and alternative traction power shown in the map below:

The plan: our decarbonised rail network in Scotland, 2035



Map of decarbonised rail network in Scotland, 2035

The maps in this document show the rail network in Scotland; as there are no rail lines on the islands they are not shown.

- (Red) Electrified network (some 1,616 kilometres (single track kilometres) to be electrified, sections of route could potentially include discontinuous electrification) and the electrification of some freight only lines may be subject to review
- (Yellow) Alternative traction - transition solution (e.g. partial electrification and/or the use of alternative technology prior to electrification)
- (Green) Alternative traction - permanent solution (i.e. the use of battery or alternative traction)

[9]

This paper identifies further electrification in Scotland as the primary solution to support a net zero emission network but acknowledges that alternative traction solutions such as

[9] Rail Decarbonisation Action Plan, July 2020

battery and hydrogen powered rolling stock can also be viable options as both interim and permanent solutions, especially in more remote areas of the network.

Energy efficiency of traction types

An **electrically powered train** is the most energy efficient form of traction. For every 1kW of power through its wheels it requires about 1.2kW from the National Grid.

A **battery train** is 12% points less efficient in its operation than an electrically powered train because of the constraints of the battery i.e., its capacity to store and release energy which impacts on its range with the weight of the battery itself having an impact on the efficiency of the train. The cost of a battery adds about one third or more to the capital cost of a similar electric train powered via a catenary system.

A **hydrogen fuel cell train** can operate over a longer non electrified route than a train with only a battery and can typically be thought of as a hybrid system, where the hydrogen fuel cell works in tandem with a battery. Refuelling with hydrogen is fast, although hydrogen tanks need to be large to take into account the increased volume required to generate the same amount of energy as diesel. Hydrogen has an efficiency rating of less than 30%.

A **diesel train** is the least energy efficient source of traction with an efficiency rate of about 26%. Diesel also produces noxious gases and particulate emissions.

Decarbonisation and Emissions Credentials

With regards to CO2 emissions, diesel traction, whether diesel mechanical or diesel electric, has the highest carbon footprint of the range of traction options and is also responsible for other harmful pollutants and particulate emissions at the point of use. Replacement of diesel is, therefore, essential to meet decarbonisation targets and also local air quality targets especially in urban areas.

Electric, battery powered, and hydrogen powered traction technologies can all deliver zero carbon emissions and zero/minimal harmful pollutants at the point of use, however, in all three cases the emissions credentials are largely dependent on the pace of the transition to clean renewable and other zero carbon sources of electricity in the power generation sector. This issue is explored further below.

Electrification benefits outside energy efficiency

Electrification is a tried and tested technology that uses energy efficiently and reduces CO_2. There are other benefits listed in the Rail Decarbonisation Action Plan noted below.

Local environmental benefits:

- Improved air quality, reduced noise and vibration

Direct passenger/freight customer/user benefits:

- journey time reductions and better connectivity and access to markets - through superior acceleration which will generate particular benefits on more hilly routes such as the Highland Main Line and towards Aberdeen from the south, and on services with frequent stops such as the East Kilbride line
- improved network capacity - as journey times for passenger and freight trains are improved by electrification overall capacity on key routes is improved; when combined with suitable signalling systems, electrification can often contribute significantly to improving the overall capacity of the network – this can allow the release of additional paths and increased services
- improved network resilience - through the electrification of diversionary routes – improving the network's performance and reliability
- substantial freight benefits - higher power allows heavier trains to operate faster and at lower cost and makes it easier to operate more freight trains between passenger trains. Options for electrification of freight sidings, if appropriate, and terminal requirements can also be reviewed during the design phases

Operational benefits:

- rolling stock strategy synergies – medium to long-term planning and certainty allows for more coherence in rolling stock strategy procurement
- lower rolling stock costs – electric trains are lighter and cheaper to build and to maintain
- improved reliability/availability/efficient use of rolling stock - as more routes are electrified, electric traction/trains in the long-term can be interchanged more easily, currently 60% of the fleet is electric
- infrastructure operating costs – economies of scale can be achieved through operating more of the same type of infrastructure
- industry fuel costs – electric grid power is around 50% less expensive than diesel, and further benefits can be realised through the use of renewable/low carbon or innovative direct feed energy for overhead line supply

Alternative traction options

The electrification programme across Scotland and the UK represents a significant investment challenge that will take time to deliver and, on some lines, especially in remote and rural areas, full electrification may not be feasible due to cost or environmental factors.

Alternative traction options will be required to achieve interim emission reductions as the electrification programme proceeds, and to secure decarbonisation of non-electrified lines. With these alternative traction options, Scotland has an opportunity to stimulate innovation within the train manufacturing industry and wider supply chains, potentially creating skilled, sustainable employment in Scotland.

Traction Combinations with Diesel

At the end of 2020, there were 148 diesel-only trains, with 394 carriages, and 203 electric units, with 649 carriages leased by ScotRail. The diesel units have a range of anticipated end of life dates (depending on class type) between 2025 and 2035. Ultimately these units will all have to be replaced to enable zero carbon targets to be achieved, but there are potential interim options for diesel traction combinations which can potentially secure carbon reductions on the route map to full decarbonisation. Some of these options are already in operation in the UK and overseas.

There are two main options for combining diesel traction with a secondary technology: hybridisation and bi-mode operation. Neither are optimal in terms of overall cost and efficiency because they rely on diesel traction at their core and the multiple drive systems and equipment add to weight, complexity and maintenance requirements. They can, however, assist in meeting interim emission targets on the path to decarbonisation.

Hybrid diesel electric trains are fitted with energy recovery and storage capabilities to create a hybrid architecture which enables energy to flow automatically to and from the energy storage system to make the most efficient use of the primary diesel power source. This approach can limit emissions overall and can specifically target lower emissions in sensitive areas or high emissions modes of operation such as acceleration.

Multi-mode diesel electric trains can switch between diesel and electric power depending on location and mode of operation. Automatic Power Change Over (APCO) can be installed in certain sensitive areas to automatically switch from diesel to electric operation.

Research has indicated emission reductions as high as 20% versus standard diesel electric operation by applying these hybrid or multi-mode technologies, but results are highly sensitive to train use patterns and ensuring diesel shutdown when not required. [10]

Ideally, new build hybrid and multi-mode diesel vehicles will be compatible for future upgrade to lower or zero emissions traction technologies, thereby ensuring that the full operational life can be achieved and avoiding significant costs of obsolescence.

Hydrogen trains

The decarbonisation credentials of hydrogen fuel cell powered trains have been summarised above. In the context of their potential as an alternative to electric traction, it is notable that they have the capability to deliver long distance services and operate on stretches of the network with no installed contact system. They are quiet, emit no pollutants at point of use, and can also be configured as bi-mode, powered by hydrogen or

[10] Traction Decarbonisation Network Strategy, Network Rail

via electric contact system. Hydrogen traction will require little change to the railway infrastructure; however, it will require potentially significant investment in new hydrogen production, distribution and train fuelling systems.

Battery Powered Trains

Battery powered trains use an electric motor traction system similar to conventional electric trains, but also carry on-board batteries with sufficient capacity to power the unit over long distances (eg up to 50 miles) between charges. As highlighted above, the additional weight of batteries, associated power convertors and cooling systems makes these vehicles heavier and less efficient than conventional electric contact trains and the higher the battery storage capability the lower the relative performance in terms of haulage capacity and speed.

Given the weight of batteries and associated power converters and cooling systems, these vehicles are heavier and less efficient than conventional electric contact trains, and the higher the battery storage capability the lower the relative performance in terms of haulage capacity and speed.

The significant advantage of these trains is their ability to operate with zero emissions at point of use over sections of the network where full electrification is not viable, eg in remote, rural or lower traffic areas. In these situations, the avoided cost of investment in continuous power supply infrastructure can outweigh the lower operational efficiency / effectiveness of the units, making them a viable option. They do require charging, but this can be delivered on limited sections of track with continuous contact, or via discrete charging facilities, or a combination of both, thereby avoiding the need for full line electrification.

Another advantage is the ability to convert conventional electric trains to battery powered units and vice versa, thereby reducing capital investment and obsolescence costs. The relative advantage of battery powered traction will increase with improving battery performance and lifespan.

New infrastructure for electric or alternative traction options

Electrification or alternative traction fleets whether hybrid, battery or hydrogen powered will require new supporting infrastructure to maintain, fuel and recharge trains including new depots and related capital equipment, to ensure availability, performance and reliability are maintained across the fleet. The development of this new incremental infrastructure can be focused around utilising, adapting and adding to existing facilities wherever possible to minimise investment requirements.

Decarbonisation: routes and services

Investment decisions will look in considerable detail at the costs, benefits, risks, timescales and choices around procurement strategies and delivery mechanisms before making an informed determination.

A rolling programme of decarbonisation considers a range of key factors and drivers such as:

route characteristics (track length, structures/structural clearances)

- service types (commuter/local, intercity, regional, freight, scenic)
- connectivity between all of Scotland's seven cities
- fleet design and economic life expiry (the current train fleet and timescales for renewal)

- an assessment of diesel trains operating on electrified routes
- whether electrification enables a diversionary route
- previous development work
- projects in the planning stages and current and future rail renewals
- passenger and freight benefits
- power requirements
- overall network impacts/flexibility (interworking of fleets)
- operational flexibility
- supply chain capability
- technical capabilities of new and emerging alternative technologies.

The major infrastructure cost components of electrification are:

- clearance of structures
- installation of overhead line electrification
- power feeding and sub-stations
- development, design and project management

Innovation in electrification schemes

piling and pile caps	wire gradient	uplift and ice loading
new feeding architectures	neutral section	Insulated pantograph horns
span lengths	reducing bridge parapets	more electrical clearances

[11]

Some more detail on some of the innovations –

Span lengths: Network Rail's current electrification designs use shorter lengths between masts than previous British Rail designs or comparable practice in Europe. Costs, programme length and disruption to passengers and freight customers during construction are driven by the number of masts. Therefore, it is necessary to give consideration to overhead equipment type, tension, how straight the track is and wind loading to increase the span length between overhead structures, minimising overall structure numbers in order to save on costs.

[11] Rail Decarbonisation Action Plan, July 2020

Parapet heights: 1.8 metre bridge parapet height is now a Network Rail standard requirement for new electrification projects, but protection to people may be provided by more cost-effective means. One such solution would be neutral sections, however they also present operating risks if a unit were to get stuck in the middle of said section. This will be a key consideration when assessing a particular bridge and its relationship with overhead line equipment (proximity to public interface) to determine if the parapet height requires to be increased. The fewer structural interventions required will drive efficiencies in both cost and programme.

Insulated pantograph horns: this initiative may enable the clearance requirement at stations and lineside equipment to be reduced without impacting safety requirements – with overall savings to cost and programmes.

Increased efficiency through digital transformation

Driving styles can have a significant influence on energy efficiency for both electric and diesel trains, especially during acceleration and deceleration stages, and hence fuel usage and emissions or electrical power draw. Digital applications such as Driver Advisory Systems (DAS) can assist drivers in normalizing their driving style and achieving more efficient operation. Analysis by RSSB has indicated that adjusting driving speed for diesel trains based on predicted journey times and avoiding high acceleration/deceleration rates could yield reductions in CO2 emissions of up to 10%.[12]

More trains will be fitted with these types of applications as the Digital Railway programmes are rolled out, and whilst the emissions saving may be relatively marginal, they will contribute to interim reduction targets especially with regard to diesel operations.

Power Supply and Quality Considerations

Rail is already the largest electricity user in the UK, with the sector consuming just over 4 Terawatthour (TWh) in 2019/20 which is broadly equivalent to the consumption of 1 million homes. Rail electrical demand will continue to grow as a clean electric, battery and hydrogen powered trains replace diesel, and also with modal substitution.

As highlighted above, the rail industry will need to take responsibility to ensure that the growing demand for electrical power for rail traction and operation of rail related infrastructure is sourced from renewable and lower/zero carbon generation sources and that it is not simply exporting the problem to other sectors.

This can be achieved, at least in part, by procurement of Power Purchase Agreements with renewable generators. There are also potential opportunities for the direct sourcing of power from local distributed renewable generation sources, e.g., solar and wind. The commercial viability of such projects may be enhanced by avoided costs of incremental investment in HV power grid and network, particularly in rural/remote areas.

Rail sector involvement in smart grid, power storage and load balancing activities can also increase the commercial viability of electrification projects whilst supporting efforts to

[12] Traction Decarbonisation Network Strategy, Network Rail

address the energy security challenge arising with growing societal demand for use of intermittent sources of clean, green electricity. New and innovative techniques will be required to make sure that there is a consistent and sufficient quantity and quality of supply

Electrification schemes in progress or planned

Network Rail has already started design development work on a number of electrification schemes to connect and consolidate the electrification of lines in central Scotland which in some instances will enable the relocation of rolling stock to assist with pressure points elsewhere on the network.

Passenger lines:

- Glasgow Anniesland (via Maryhill)
- the Borders line
- Levenmouth and other discrete sections in Fife
- South from Glasgow to East Kilbride, Barrhead and Kilmarnock
- Fife and mid Scotland

Network Rail is undertaking development and design work in 2020 for routes in Fife (from Edinburgh Haymarket to Fife/Dundee) reviewing the constraints and opportunities in this area. The aim is for a continuous electrified line of route from Edinburgh through Fife to Dundee and Aberdeen to the benefit of passenger and freight services. Some (early) discontinuous electrification may be appropriate for the wider Fife lines. Design and development work will also be progressed in 2020 for the route from Dunblane to Perth.

Scotland's rural network

Based on fleet expiry dates, and rolling stock interworking, the Far North Line, West Highland Lines and Kyle Line are considered appropriate for the early introduction of an alternative traction technology as a permanent solution. This workstream will be expedited and routes considered together as a package while taking account of the distinct requirements of each of the lines.

North-East Scotland

The North East of Scotland will require alternative traction technologies until electrification works are planned, funded and delivered on appropriate routes.

Connecting Aberdeen and Inverness to the Central Belt

By 2035, the plan is that there are fully electrified routes from the central belt to both Aberdeen and Inverness east. The length of these routes, potential planning constraints, complexity of programme and power requirements, and the need to coordinate workbanks means that early development work on these routes will start in advance of when passenger trains enter into service. Alternative traction may be used during the transition from the central belt to Aberdeen if it aligns with Aberdeen to Inverness rolling stock requirements, and subject to sufficient advancement of alternative traction technologies.

Inverness to Aberdeen

Though plans are to electrify the entire route, the current programme, predicated on an average annual implementation rate of single-track kilometres, indicates that the section from Aberdeen to Inverurie may only be electrified by 2035. However, as new, innovative approaches develop, the pace of implementation and the industry's capability to deliver may increase further and allow full electrification of the route by 2035. In the interim as technologies advance, alternative bi-mode traction will be needed with an expectation that the route will be fully electrified shortly after 2035.

South-West Scotland

By 2035, the aim is to have an electrified route between Glasgow via Gretna to Carlisle benefitting commuter flows from New Cumnock to Glasgow and Dumfries to Carlisle. Additionally, electrification of the line is expected to provide an enhanced strategic capability for rail freight, and a valuable diversionary route for freight and passenger services during closure of the West Coast Main Line. Alternative traction will be used as a transitionary measure in the South-West of Scotland until full electrification is delivered and also on the line from Ayr to Girvan. At this stage, it is thought that alternative traction will run permanently from Girvan to Stranraer.

The overall aim is to electrify, on average, 130 single track kilometres per year in order to achieve the 2035 target. As part of this project there will be significant prospects for the creation of more skilled, sustainable jobs in Scotland and, accordingly, a significant additional contribution to the economy. These jobs will be in the direct provision of electrification as well as in the supply of rolling stock and advanced technologies and in the design of alternative traction methods to complement electrification of the network.

Wider implications for rail

While the scope of this action plan is the decarbonisation of domestic passenger rail traction, there is an expectation that all parts of the rail industry, including Network Rail, train and freight operating companies and rolling stock providers, will produce plans to achieve both interim and long-term targets towards broader industry-wide decarbonisation.

There is an acknowledgement that some services such as the Caledonian Sleeper and heritage railway services, which bring substantial value to the Scottish economy, may be unable to electrify their traction by 2035. These services constitute less than 0.2% of total rail services in Scotland.

Conclusions

The aim of this technical overview paper is to provide a succinct outline of the scale of the task required to meet Scotland's targets to de-carbonise passenger rail journeys, and as a result underline the substantial opportunity to a wide range of engineering manufacturing and service providers that this programme of activity can provide.

The scope of works involved shows that innovation and efficiency will be essential to meeting the cost constraints that accompany any long-term major infrastructure projects such as this, and in this respect companies who typically operate outside of the rail sector may be able to take expertise from their own sector and apply it for efficiency and gains in these tasks.

For this, the Rail Cluster team would like to hear from any SME company who believe they have something to add for this challenge, and we would welcome the chance to advise and connect those companies to the support programmes available.

Resources

1. **Rail Decarbonisation Action Plan, Transport Scotland** - https://www.transport.gov.scot/media/47906/rail-services-decarbonisation-action-plan.pdf

2. **Traction Decarbonisation Network Strategy, Network Rail -** https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf

3. **RIA Electrification Cost Challenge, March 2019 -** https://www.riagb.org.uk/RIA/Newsroom/Stories/Electrification_Cost_Challenge_Report.aspx

4. **The Future of Rail, IEA** - https://www.iea.org/reports/the-future-of-rail

5. **National Transport Strategy Delivery Plan 2020 – 2022 -** https://www.transport.gov.scot/media/48839/nts-delivery-plan-2020-2022.pdf

6. **National Transport Strategy 2, Transport Scotland** - https://www.transport.gov.scot/media/47052/national-transport-strategy.pdf

7. https://www.railbusinessdaily.com/cost-efficient-electrification-the-railway-industry-continues-to-meet-the-cost-challenge-of-electrification-through-research/

8. https://www.railengineer.co.uk/electrification-and-the-environmental-challenge/

9. https://www.theengineer.co.uk/on-track-advances-uk-hydrogen-rail/