,

A Review of Recent Developments in Energy Storage and Drive Systems for Self-powered Electric Rail Vehicles

A Report for the Scottish Association for Public Transport

David Murray-Smith

Honorary Senior Research Fellow
and Emeritus Professor of Engineering Systems and Control,
James Watt School of Engineering, University of Glasgow

Email: David.Murray-Smith@glasgow.ac.uk

19th November 2025

Abstract: Building on two publications from 2019, this report reviews developments that have taken place over the last six years in energy storage and electrical drive systems for self-powered railway, light-rail, and tramway vehicles. These can incorporate electrical batteries, supercapacitors, hydrogen fuel cells, electromagnetic storage systems, and mechanical devices such as flywheels, together with control and energy management sub-systems. As in the earlier reports, each type of system is discussed separately, but some emphasis is given to developments in hybrid systems involving combinations of power sources and to associated design optimisation issues. Railways provide an important application area for short-term energy storage, especially in the context of the growing interest in discontinuous electrification schemes. Published reports and papers that describe recent operating experience and problems encountered in the use of newly designed and converted vehicles provide valuable information, and several of these are referenced. Promising research and development work is also summarised, and an attempt is made to predict future trends. Four appendices provide more detailed information about recent rail applications and also current proposals.

Keywords: Railways; tramways; energy storage; battery; hydrogen fuel cell; electrical double-layer capacitor; mechanical systems; design optimisation.

CONTENTS

1. Introduction

This report provides an updated review of issues discussed in reports prepared in 2019 for the Scottish Association for Public Transport (SAPT) entitled *"Powering Future Transport in Scotland"* [1] and *"A Review of Developments in Electrical Battery, Fuel Cell and Energy Storage Systems for Railway Applications"* [2]. Some of the material in those earlier reports was included in talks on transport issues given to members of SAPT and others in 2019 and 2024.

As was the case in [2], this new report focuses on rail transport, specifically examining recent developments in short-term energy storage technology and electrical drive systems. This is not a new area of interest, as concerns about exhaust emissions have led government bodies and railway operators to take steps already to minimise some potentially harmful effects. The current plans are to replace diesel traction with other forms of motive power, usually through conventional electrification schemes. Although significant parts of the rail network in Scotland are electrified and further mainline electrification is imminent, it is now proposed that extensive use should be made, in the short term at least, of discontinuous electrification to reduce the need for expensive infrastructure changes and thus reduce electrification costs. This represents a gradual shift of policy since the earlier reports ([1], [2]) were published, and has further focused attention on other forms of traction and energy storage methods. Scotland also has important secondary non-electrified rail routes in areas with low population densities, and current Scottish and UK Government decarbonisation targets require that diesel-powered trains should, in due course, be eliminated from passenger services. Still, it is unlikely that conventional electrification could be a cost-effective solution for such services, and it should be noted that similar situations exist on some secondary routes in England and Wales and in other countries. The target for the elimination of diesel passenger trains in Scotland was 2035, but in December 2024, it was announced by the Scottish Government's Cabinet Secretary for Transport that the timescale had been extended to 2045.

For secondary routes, the possibilities include battery-powered trains or trains equipped with conventional electric traction systems for use on electrified sections of the route, and battery packs for use on the non-electrified sections. Other options could include electric traction with a secondary diesel engine or a secondary diesel engine combined with an electrical storage system, such as a battery pack. Such bi-mode or tri-mode solutions do not eliminate carbon emissions but could reduce them, especially if biofuels or synthetic fuels were used. Other possible configurations include hybrid systems with hydrogen fuel cells and batteries (or supercapacitors) and the use of hydrogen as a fuel for internal combustion engines. There is also increasing interest, globally, in electrical and mechanical systems for energy recovery from train braking using on-vehicle or trackside systems.

Recent developments in power electronic systems and control systems technology are also important for the rail industry. The optimisation of powertrain systems to allow for bi-mode or tri-mode operation is challenging, but close similarities exist with design optimisation issues encountered in powertrain design for other types of transport, such as electric cars, buses, road freight vehicles, ships, and aircraft.

The report aims to highlight technological developments in relevant areas since the previous reports ([1], [2]) were completed. It builds on reviews published over the past decade relating specifically to railway applications of electrical storage devices and fuel cells (e.g. [3]-[7]). The steps taken to bring modern self-powered electric trains and light rail vehicles into service are discussed, with examples given of some successful projects, prototype systems currently under test, and some examples of problems that have been encountered.

One important issue that arises in railway applications is the high-vibration level that can be experienced on trains. This introduces problems of reliability and is a topic on which further development work is needed. Another factor is that performance specifications for new train designs for secondary routes are often based on existing schedules for diesel multiple-unit trains. Some question whether locking performance in this way to existing diesel multiple unit (DMU) schedules is wise when modern battery-powered trains could provide performance benefits through improved acceleration and braking.

One notable development in recent years is the attention now being given to the overall life cycle assessment (LCA) of powertrain components. This approach is often combined with techno-economic analysis (TEA) and involves making quantitative estimates of the costs, both financial and environmental, of production for each element within a powertrain, as well as the corresponding operational costs, lifetime expectations, and the eventual costs of recycling or disposal. The approach enables informed quantitative comparisons to be made of available options. Useful sources of information on LCA and TEA methods and their applications may be found in a recent book edited by Agarwal and Biswas [8].

It is significant that, in discussions about different modes of transport, relatively little emphasis is given to the potentially harmful effects of particulates and other pollutants such as oxides of nitrogen. This topic received some attention in [1]. In the years since that report was published, medical evidence has increasingly supported the view that particulates are particularly damaging to human health. While it was recognised by 2020 that particulates measuring 2.5 μm or less are a significant hazard, it is now increasingly believed that smaller metallic nanoparticles present even greater dangers. Medical evidence suggests that there is no safe concentration level in the atmosphere for metallic micro- and nano-particles, as these are linked to brain damage in humans and especially to Alzheimer's disease and other neurodegenerative disorders (e.g. [9]). Nanoparticles associated with air pollution have also been found in other human organs. It is therefore argued that more should be done to eliminate or reduce the concentration of these harmful pollutants. Although road transport of all kinds receives particular attention in this respect, with particles from exhausts, tyres, brake pads and road surface dust being recognised as particular problem areas, it must also be recognised that railways and light rail systems also contribute to metallic particulates in the atmosphere. This results from diesel exhaust emissions, brake pad wear and wheel-to-rail contact. Government recommendations regarding possible "safe" concentrations of metallic nano-particles have not yet been published. Research and development work is urgently required to investigate how the situation could be improved generally and to establish the contribution that modal shift from road to rail and tramway systems could make in densely populated areas where the problems are most severe.

The subsequent sections of this report are organised as in [2]. They include information about some new developments in electrical battery technology (Section 2), new developments in other electrical storage devices known as supercapacitors (Section 3), new developments in use of hydrogen and fuel cells (Section 4), developments in other short-term energy storage systems (Section 5), and developments in the design methods used for powertrain systems (Section 6). Information about recent progress with railway, tramway, and light-rail applications is included within each of those sections. Section 7 provides further discussion on these topics, including general issues of storage and recovery of braking energy, and Section 8 presents brief conclusions. Four appendices provide more detailed information about recent developments, especially in battery, supercapacitor and fuel cell applications, in the context of railways, light rail systems, and tramways in various parts of the world.

2. Recent developments in electrical battery technology

Several factors are important when comparing different types of batteries for transport applications, as stated in [2]. These include fundamental issues such as energy and power ratings of batteries, the energy density (energy supplied per unit volume (Wh/l)), and the power density (rated output power per unit volume (W/l)). Considering battery mass, the key measures are specific power (W/kg) and specific energy (Wh/kg). Also important are the charge and discharge power levels, typical charge and discharge times, the characteristics of different battery types in terms of "round-trip" efficiency values (energy output divided by energy supplied during charge), and self-discharge rates. Cycle life (where one cycle represents a single charge and discharge sequence) and overall lifetime must also be considered.

Batteries suitable for transport applications can be categorised according to the chemistry involved and the physical characteristics of the battery. In broad terms, they can be divided into lead-acid batteries, nickel-cadmium batteries, lithium-ion batteries, and nickel-metal hydride batteries. Some other types, such as flow batteries, are not currently suitable for on-board rail applications at present due to their size and complexity.

Although lead-acid batteries are widely used for starting diesel engines and providing auxiliary power on trains, they are no longer considered suitable for traction purposes, and nickel-cadmium batteries and various forms of lithium-ion batteries are now more common.

The structure of lithium-ion batteries involves an anode, electrolyte, separator, and cathode, as described in [2]. The separator structure between the anode and cathode facilitates ion movement but impedes electron movement, thus reducing the risk of internal short circuits. Traditional electrolytes are lithium salts dissolved in organic solvents. Different types of lithium-ion batteries are characterised according to the materials used for the anode and cathode. Although the detailed characteristics depend on the chosen chemistries, they all have high energy density, high efficiency, and low self-discharge rates.

The fundamental principle of lithium-ion batteries involves "intercalation" and "deintercalation" processes, which relate to the insertion and extraction of lithium ions into and from the crystal structure of the electrode materials. During charging, lithium ions are extracted from the anode, move through the electrolyte and separator by diffusion and are intercalated into the cathode. During discharge, lithium ions are deintercalated from the cathode and migrate to the anode. While the lithium ions move through the electrolyte, electrons flow through any external electrical circuit connected between the anode and cathode.

There are many sub-classes of lithium-ion batteries. Some of these include lithium-iron phosphate batteries (LFP), lithium manganese oxide (LMO) batteries, nickel cobalt aluminium (NCA) batteries, nickel manganese cobalt (NMC) batteries, and lithium titanate oxide (LTO) batteries. Within the battery industry, blends involving other combinations of chemistries are appearing, which are claimed to give superior battery performance compared with more conventional chemistries. However, in most cases, little information is available about these blends, for reasons of commercial confidentiality. Similarly, there are interesting commercial developments such as the Blade Battery developed by BYD. Although basically an LFP-type battery, the Blade is claimed to have significant advantages in terms of safety, as a result of its shape and improved cooling efficiency. In general terms, disadvantages of lithium-ion batteries include their high cost, relatively high risks of thermal runaway with some chemistries, and their dependence on scarce materials that are mainly found in a few key areas around the world.

NMC batteries give a high energy density and long cycle life, but the cathode materials depend on the mining of nickel, manganese, and cobalt, and there are environmental issues for all of these metals. The same is true of NCA and LTO batteries, but the cathodes in LFP batteries involve sources of iron and phosphates, which are more abundant and less difficult to mine. However, this type of battery gives an energy density that is lower than for the other types. Currently, NMC, LFP, LTO and NCA batteries seem to be favoured for heavy transport applications, such as railways.

Present-day research and development work on lithium-ion batteries mainly addresses issues of energy density, safety, lifespan, recycling, and environmental issues linked to lithium mining and processing. Investigation of new chemistries, and especially new materials for electrodes, together with novel methods for electrode manufacture, are vital areas of research. Research efforts on fault detection, battery system optimisation, battery degradation, thermal stability, and ways of preventing thermal runaway are also important. These are areas in which modelling and simulation techniques are now being used routinely in battery research and development worldwide. The testing and validation of battery models is, therefore, being recognised increasingly as an important activity. Other areas of continuing concern include the adverse environmental effects of mining and materials processing for some types of batteries, battery life expectancy, total energy efficiency (including the energy used in battery manufacture and end-of-life disposal), and cost.

Specific energy densities for currently available lithium-ion batteries are about 300Wh/kg, with a commonly quoted target figure of at least 400Wh/kg for future developments. The cycle life is expected to rise from about 3000 to more than 5000 cycles [10]. Cost is a factor of critical importance for all applications. It should be noted that, in 2010, lithium-ion battery prices were around $US 750-1000/kWh with specific energy densities of 110Wh/kg. By 2024, the global average price of lithium-ion battery packs was $US 115/kWh [11].

Improvements in our understanding of chemistries for new types of batteries, such as sodium-ion batteries, metal-air batteries, and the development of solid-state electrolytes that are inherently safer than liquid electrolytes, are important research topics. More speculative areas currently under investigation include the use of graphene and biomimetic materials. Graphene, which involves a single layer of carbon atoms arranged in a hexagonal lattice, is a very thin, very light, and extremely strong material that has very high electrical and thermal conductivities. It is of interest to battery researchers since it is believed that its use could lead to improvements in battery performance through higher energy density, enhanced efficiency, longer life, and faster charge and discharge rates with reduced risk of fires and explosions. Another benefit of this material is that it is derived from carbon, and the development of graphene batteries would reduce the use of scarce and environmentally harmful materials in battery manufacture [12]. Biomimetic batteries mimic processes found in living organisms, and the research could lead to the development of new energy storage methods and materials that overcome some of the current problems being encountered with more conventional forms of battery [13].

Other areas of research on battery systems include work involving detailed design improvements that optimise battery efficiency, longevity and safety, together with developments in terms of innovative manufacturing methods. Developments in more energy-efficient recycling techniques are also important to ensure that the industry can become less dependent on precious resources currently sourced from abroad.

2.1 Rail applications of electrical battery technology

The development of electrical batteries suitable for rail traction applications is linked closely to other application areas. Ideally, for railway and light rail applications, batteries should have high power and energy densities and be able to operate for between 10000 and 30000 charge and discharge sequences per year [7]. This good cycle life should be combined with a long battery lifetime. Experience with the use of battery power in other forms of transport, such as buses, trucks and ships, is highly relevant. Much research and development work on electrically-powered aircraft has also been reported during the last five years, with some important milestones having been reached and reports published (e.g. [14]).

Several useful review papers on energy storage and the use of electrical batteries, supercapacitors, and hydrogen fuel cell systems that deal specifically with issues relevant to the railway and light rail sectors have appeared in recent years. These include reviews published by Fidele et al in 2021 [5], by Saeed et al. in 2023 [6], and by Dominguez et al. in 2025 [7]. These supplement earlier reviews of progress in the same fields (e.g.[3], [4], [15]).

One area of major concern relates to thermal runaway situations, and a recent paper by Lee et al. [16], published in 2025, addresses such issues. The results of simulation studies suggested that high ambient temperatures and low cooling efficiencies increased the risks of thermal runaway significantly. Another paper by Meng et al. [17], published in 2024, considered aircraft applications and, through experimental investigations, showed that under low pressure and low temperatures, the risks of thermal runaway could be reduced significantly.

Much emphasis is now being placed in many parts of the world on discontinuous or intermittent electrification, where gaps are incorporated within the overhead catenary or third rail supplies, and electrical batteries are used to power trains over those non-electrified sections. This growth of interest in the use of intermittent schemes to reduce the cost of new electrification programmes has been reflected in new attention being given to battery performance limitations and to different battery chemistries. Some recent papers highlight these discontinuous electrification strategies (e.g. [18] - [20]), but commercial sensitivity issues abound in terms of information about battery power ratings and storage capacity, and this significantly limits the details made available concerning some train performance test results. However, information provided may allow some estimates to be made of performance limitations and the reasons for these limits. For example, some train designs do not allow batteries to be charged from the catenary while the train is on the move. This appears to be associated with maximum catenary currents in the existing infrastructure. This problem could be overcome, in part, by enhancing the existing catenary, but one must ask whether the cost of upgrading the electrified sections would be much less than the cost of conventional electrification of the complete route.

A recent paper by Ruvio and Bayrak [21] addresses design issues for a high-speed train application, and a paper by Shrestha and Stuart-Smith [22] considers the specific case of the 261 km route between Tocunwal and Appleton Dock in Australia. This line involves some sections with steep gradients, and options for electrification considered include electrification of the most CO2-emitting sections of the route (i.e. those involving high power demands due to rapid acceleration, high speed cruising and steep rising gradients) or electrification only of the steeply graded sections. Two motive power options are considered, involving diesel-electric or battery electric systems. The findings relate very specifically to the route considered, but the options considered are of general interest.

2.2 Developments in battery technology for rail applications within the United Kingdom.

In the UK, interest has been growing recently in the use of batteries for trains, trams, and other light rail vehicles. This section provides a brief overview of a few developments that have taken place in recent years. Details of these, and other developments in battery-electric trains and light rail vehicles in the UK, may be found in Appendix A, which provides more examples. However, this is not intended to be a comprehensive list of all UK projects involving battery electric vehicles.

As pointed out previously [1][2], this interest is not new and dates back many decades to a relatively successful project started in the late 1950s in Scotland, which saw a battery-electric multiple unit (BEMU) in regular timetabled passenger service between Aberdeen and Ballater. Some details of that vehicle and its performance may be found elsewhere [23].

Discontinuous electrification is seen as a way of reducing the cost of electrification schemes in the UK, and Stadler has already provided a fleet of seven bi-mode electric/battery-electric trains for the short non-electrified Merseyrail route between Kirby and Headbolt Lane [24]. That company is also supplying battery-electric/diesel trains for Transport for Wales [25]. Several other train manufacturers have been putting forward proposals for trains with battery provision, and Chiltern Railways published tender notices in September 2022 for between 30 and 70 new battery-electric multiple units [26]. Also, a market engagement notice was published in July 2025 for the procurement by ScotRail of 28 bi-mode battery electric multiple unit trains as part of a larger train order, with deliveries to begin in 2030 [27].

Important developments have also been taking place in the area of fast charging of battery-electric trains. The Vivarail company, which was developing battery trains and associated fast charge facilities, went into administration in November 2022. Its assets, in the form of rolling stock and intellectual property associated with the development of the fast charge technology and high-performance battery systems, were purchased by the train operating company Great Western Railway (GWR). This allowed the development work to continue, and a three-car unit was tested extensively on the 2.5-mile-long branch line between West Ealing and Greenford for about one year, ending in July 2025. Results suggest that fast-charge battery trains could be a viable option for GWR for branch lines currently operated by that company in the Thames Valley, Devon, and Cornwall [28].

The Vivarail solution for fast charging is not the only development in that area of technology in the UK. Siemens Mobility launched its new Rail Charging Converter (RCC) in June 2025. This development received funding from Innovate UK and Porterbrook, and much of the work was carried out at Porterbrook's Long Marston Rail Innovation Centre. Siemens Mobility claims that RCC equipment can be installed in 18 months, without any need for direct connection to the 275/400kV power distribution network, as it is based on lower voltage connections to the local electrical supply. It is claimed that the RCC can fully charge a train in 20 minutes and is ideal for discontinuous electrification schemes (e.g., [29]).

Another notable development in the UK is the project for Very Light Rail (VLR) being undertaken in Coventry, which involves battery-electric traction (e.g., [30]). In other developments, there is a project underway for the development of a new design of battery-powered shunting locomotives, and other projects involve the conversion of diesel-electric shunting locomotives to incorporate battery packs in place of diesel engines.

2.3 Developments in battery technology for rail applications in other parts of Europe and elsewhere.

Although no trains powered only by batteries are currently in regular service in the UK, the situation in other parts of Europe is different, and this section is intended to provide a summary of some selected recent developments. Further details of these innovations and information about other developments may be found in Appendix B of this report.

In Germany, several manufacturers have battery-electric trains in service or are expected to have their products introduced in the near future. One example was the introduction of Stadler *Flirt Akku* two-car BEMUs in the state of Schleswig-Holstein [31]. To allow BEMUs to operate on lines that are not electrified, three "electrification islands" are now being created, and the same is happening in the Sachsen region. Siemens *Mireo Smart Plus B* Class 536 BEMUs were expected to enter service on regional routes in the Offenburg area in the Black Forest in December 2024 and additional trains of this type were on order in January 2024 for services in Brandenburg near Berlin [32]. In addition, Alstom *Coradia Continental* BEMUs were expected to appear on services between Leipzig and Chemnitz in 2024, and CAF is building a fleet of *Civity* BEMUs for use in the Ruhr region.

Siemens *Mireo Smart Plus B* BEMU trains received authorisation to operate on the Danish rail network in July 2025 and entered service with limited passenger operation [33]. Also in Denmark, Sjælland regional council is investing in 24 Stadler *Flirt Akku* BEMUs for Lokaltog for use on the Odsherredsbanen between Holbæk and Nykøbing Sjælland [34].

In France the battery hybrid version of the *Régiolis* DMU entered service on the Toulouse-Castres- Mazamet route. Most of the line to Mazamet is not electrified and it is assumed that the battery packs will be used to boost the power from the diesel engines [35].

In Italy, Trenitalia has launched inter-city four-mode hybrid trains with diesel engines, overhead electric power via a pantograph, and on-board batteries on the route from Tarantalabria to Reggio di Calabria [36].

Other recent developments include the announcement by Czech Railways (ČD) of an order, in mid-2024, for 15 BEMUs from the Škoda Group, following an earlier order for four BEMUs which were due to enter service in December 2024 [37]. In Ireland, the Dublin Area Rapid Transit (DART) network ordered thirteen 5-car BEMU sets from Alstom in December 2021 to allow operations beyond the limits of the currently electrified network [38].

Developments in battery-powered shunting locomotives are underway in several places in Europe involving Vossloh [39] and other locomotive manufacturing companies.

There are now many examples of battery use on tramways and light rail systems, especially where there are areas of cities where it is thought that the addition of catenary would be detrimental in terms of the historic environment.

Developments in North America include the ordering from Stadler by the Chicago commuter rail operator Metra of eight battery-electric *Flirt* trains for delivery in 2027-28 [40].

3. Recent developments in electrical energy storage using supercapacitor technology

Supercapacitors (also commonly known as "ultracapacitors") have electrical properties similar to conventional electrolytic capacitors but have much higher energy storage capabilities and lower internal resistance [2]. These devices have a significant advantage over batteries for energy storage in some transport applications in that they can provide very high output power levels for short periods of time, and the time required for charging is very short. This makes them particularly suitable for use in regenerative braking systems.

There are three types of supercapacitors [41]. The first of these is known as an electrical double-layer capacitor (ELDC), and in this type of device, energy is stored in an electrical double layer created at the interface between an electrolyte and a conductive electrode. No chemical reaction is involved, and the process is based simply on the adsorption and desorption of ions from the electrode. The second type of capacitor involves the storage of electricity through an electrochemical process and is known as an electrochemical pseudo-capacitor. It uses conducting polymer or metal oxide electrodes and, essentially, it falls between an electrical double-layer type of device and a battery. The third type of supercapacitor is known as a hybrid capacitor and involves charge storage mechanisms that are both electrochemical and electrostatic. The anode is similar to those in lithium-ion batteries, and the cathode uses activated carbon and is essentially the same as those used in other supercapacitors. They have a larger capacitance than the electrical double-layer type of supercapacitors and lower self-discharge currents.

Most rail applications to date have involved ELDC supercapacitors. They have a specific power output that is almost ten times greater than batteries that are currently available. They also have minimal maintenance requirements. However, they have lower specific energy (typically 5-10 Wh/kg) compared with batteries (which, typically, are in the range 100-200 Wh/kg). They are therefore most suitable for applications involving short periods of time when they provide high power output levels and short periods when they are required to absorb energy (as in regenerative braking). The charge/discharge cycle lifetime for supercapacitors is between 10^5 and $10^{6,}$ which compares very well with the typical figure of between 500 and 10^4 cycles for batteries.

The use of supercapacitors in regenerative braking has attracted much attention in recent years. A paper by Partridge and Abomelamaimen [42], published in 2019, provides useful information based on findings from a test rig, but suggests that there are fundamental limitations in the use of supercapacitors for regenerative braking applications because the capacitance of a supercapacitor depends on the charge and discharge rates.

Supercapacitors are often used together with other electrical storage devices (e.g. Li-ion batteries) to provide hybrid systems that offer both high specific power and high specific energy. This offers low vehicle emissions combined with the rapid charging and controlled discharge that supercapacitors provide. Due to the high specific energy of batteries and the high specific power of supercapacitors, these devices offer distinctly different design options for powertrain systems, and there are possible advantages in using them together. In addition, compared with a battery-only design solution, the longer life of supercapacitors can be a significant factor.

One advantage of ELDC supercapacitors is that the materials used in their manufacture are environmentally friendly. Also, the safety level is high compared with lithium-ion batteries, as there are no issues associated with overheating and thermal runaway. Maintenance costs are low, and the cycle lifetime in terms of the number of charge/discharge events is almost unlimited. Unlike batteries, supercapacitors allow deep discharges to occur (even from 100% to 0% state of charge) without damage being sustained. Although specific energy levels are lower than for batteries, the high specific power of supercapacitors allows very effective short-term storage of energy [43]. The cost of supercapacitors has fallen by 65% to 75% over the past fifteen years and is expected to fall further, but the cost of batteries is also expected to fall significantly. Research on the use of graphene and other carbon-based materials for electrical double-layer capacitors is showing progress [44], [45].

Following tests of supercapacitor technology that started in Germany in 2003, some practical experience has been gained in Europe, and elsewhere, from applications involving trams, other light-rail vehicles, and trains. Supercapacitor technology has also been used for short-term energy storage on hybrid diesel-electric multiple units and can be used for track-side energy storage on electrified routes. Developments in the context of rail applications are discussed in some detail in papers published in 2021 by Navarro et al. [46] and by Chen et al. [47]. Several cities in China are using trams manufactured by the CRRC Corporation that use supercapacitors, which are charged while at rest at stations.

4. Recent developments in hydrogen and fuel-cell technology

A key factor that is making hydrogen potentially attractive as a fuel and for energy storage is that the energy density of hydrogen is high. Also, vehicles using hydrogen fuel can be refuelled faster than an equivalent battery-powered vehicle. On the other hand, hydrogen is a highly flammable gas and potentially explosive. This introduces additional challenges for vehicle designers and for the transportation and storage of the gas.

Options for hydrogen as a fuel for transport applications include the direct use of hydrogen in internal combustion engines and use in hydrogen fuel cells. A useful general comparison of these approaches can be found in a recent book chapter by Kakati and Ramadhas [48]. In terms of railway applications, the use of fuel cell technology is currently the norm, although there is at least one example of a project (in Ireland) involving internal combustion technology, as outlined in Section 4.3.

As discussed in detail in [2], fuel cells convert chemical energy into electricity through an electrochemical reaction. They require a continuous source of fuel (such as hydrogen) and oxygen (usually from the air). Although hydrogen is generally regarded as a “clean” form of energy, this is true only if the hydrogen is generated from water by electrolysis, using electricity from renewable sources such as wind or solar power.

The voltage output of a fuel cell decreases as the load current increases, due to a combination of activation loss (an electrochemical effect), internal resistance issues, and mass transport losses caused by depletion of reactants at the anode and cathode. In addition to electricity, fuel cells produce water, heat, and small amounts of other emissions. The energy efficiency of a fuel cell is generally between 40–60% but overall efficiencies of up to 85% may be achieved if waste heat can be utilised.

Polymer electrolyte membrane fuel cells (PEMFCs) are being used increasingly for a range of applications, including transport. In these cells, hydrogen releases electrons and creates hydrogen ions at the anode. The hydrogen ions pass through the membrane, and oxygen reacts with these hydrogen ions and electrons to produce water at the cathode. Electrons flow through any external electrical pathway between the electrodes [2]. Compared with other types of fuel cells, PEMFCs show high power densities and rapid start-up times.

There has been a growth of interest in recent years in PEM fuel cells that operate at temperatures between 150 and 180°C, as these offer high power conversion efficiencies and lower operating temperatures and are designated as High-Temperature PEMFCs (HT-PEMFCs). These are seen as potentially important as they could allow hydrogen fuel cells to be designed that offer high power densities and good operational efficiency in harsh environments and involve materials that do not carry high environmental risks [49]. Much work needs to be carried out to move the technology forward from laboratory prototype HT-PEMFCs to full-scale production, but future developments in this field could be important for transport applications.

Research continues on other forms of fuel cells that do not use hydrogen. One interesting area relates to microbial fuel cell technology [50]. Such devices are intended to convert biomass and organic waste into electricity. Current problems with this technology relate to the low power output levels that are currently obtained and the high operational costs. Promising areas of research to address these difficulties include improvements in membrane design and the use of nanomaterials to improve efficiency.

A recent review paper by Singh [51] includes a discussion of the principles of various forms of fuel cells and the potential in terms of developments in new areas of science and engineering, such as the use of cryogenics and storage of hydrogen in liquid form to improve the energy density. It also discusses some of the current limitations of hydrogen fuel cells as power sources, such as the small-scale production and very restricted refuelling infrastructure, the high capital and operating costs of hydrogen-powered vehicles, the lack of national policies concerning the use of hydrogen, the slow progress in establishing appropriate regulations, the low level of efficiency in the production of green hydrogen using electrolysers and the issues that arise in the transportation and storage of hydrogen. Additional challenges relate to fuel cell durability and the estimation of life-cycle emissions to allow quantitative comparisons to be made with other technologies, such as batteries, for transport applications.

Issues of safety attract a lot of attention from the public whenever hydrogen is discussed as a fuel of the future. A recent report by Wang et al. [52] provides much interesting information, although it is concerned with buses rather than rail transport. Many of the findings do, however, appear to be highly relevant for the rail industry and could help establish procedures for the operation of hydrogen-powered trains, especially in enclosed areas such as stations, tunnels and maintenance sheds.

4.1 Rail applications of hydrogen technology

Hydrogen fuel cell technology is widely seen as a promising long-term solution for many transport uses. Valuable experience is being gained in several cities, including some in the United Kingdom, from hydrogen-fuel cell-powered buses that are in regular service.

A report published in 2019 by the Institution of Mechanical Engineers [53] suggested that hydrogen power should be considered for rail transport applications mainly for regions close to where hydrogen is produced from renewable energy sources, leading to the creation of ‘clusters’ of hydrogen-related businesses. Thus, large-scale hydrogen production might be most suitable for more remote areas with reliable sources of wind or solar energy and also poor connections to the main electrical power distribution networks. Most of the conclusions of that report appear to remain valid today.

A very significant international development completed within the period since the earlier reports is the Fuel Cell Hybrid PowerPack for Rail Applications (FCH_2RAIL) project. The partners in this are, from Spain: RENFE Operadora (RENFE), Construcciones y Auxiliar de Ferrocarriles (CAF), Administrador de Infraestructuras Ferroviarias (ADIF), and Centro National de Hidrógeno); from Germany (German Aerospace Centre (DLR) and Stemman Technik); from Belgium (TOYOTA); and from Portugal (Infraestructuras de Portugal). The project received support from the European Union’s Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research. The final event in this project took place in Zaragoza in November 2024 where presentations were given by various speakers on the project's technical background (the FCH_2RAIL project coordinator (from DLR) and the FCH_2RAIL Technical Coordinator (from CAF)), the operator’s technical perspective (from RENFE), the ADIF authorisation experience (from ADIF), an account of the train demonstration in Portugal (from Infraestructuras de Portugal), the train manufacturer experience (from CAF), fuel cell modules in rail applications (from TOYOTA), testing of the fuel cell hybrid power pack and development of the hydrogen refuelling system (from Hidrógeno), an investigation of alternative cooling/heating technologies (from the Wabtec Corporation), methods and tools for hybrid trains (from DLR), a normative framework and networking for hydrogen in railway vehicles (from Hidrógeno), and, finally, a project summary (by the Project Coordinator, a DLR representative) [54]. Much detailed and useful information may be found in the presentations from that final event in 2024 and in other reports and papers published on the work and referenced through that presentation website. Additional details of the published results from this work are included in Appendix D.

A recent paper by Bu et al. [55] considers energy management issues in a hydrogen hybrid powertrain for an intercity multiple-unit train. It is of particular interest because it considers the use of both fuel cells and hydrogen-powered internal combustion engines in hybrid configurations with lithium-ion batteries. Simulation studies are based on specific powertrain configurations involving a lithium-ion battery pack and either two 240kW fuel cell modules or two 240 kW hydrogen internal combustion engine modules.

Other recent reviews include papers by Ding and Liu (2024) [56], Marjani et al. (2023) [57], as well as a review by Sun et al. in 2021, which includes a useful account of earlier work [58]. These papers bring together some up-to-date information about technical and economic issues that currently make hydrogen an unattractive option for rail transport applications, but also point to engineering developments in fuel cells and in hydrogen production and distribution methods that may change this situation. The paper by Marjani et al. [57] includes a discussion of simulation results for the route between Manchester Airport and Barrow-in-Furness. A paper by Peyrani et al. (2025) [59] focuses attention on the use of hydrogen for regional trains, while those by Correa et al. [60] and by Ngadi et al. [61] consider issues of locomotive-hauled trains and freight transport.

Safety issues are, of course, of particular importance in all applications involving hydrogen. A recent paper by Xu et al. [62] highlights the numerous gaps in research on the safety of hydrogen-powered trains. It is generally accepted that the unintentional release of hydrogen in an open outdoor situation will result in very rapid dissipation of the gas, thus posing little risk. The most dangerous situations are thought to be in confined environments, such as tunnels, stations, and maintenance sheds, and many similar situations exist for road vehicles. In the case of bi-mode rail vehicles involving conventional electric traction together with hydrogen fuel cells, any hydrogen leakage close to pantographs and overhead catenary could be a significant risk due to sparks causing ignition of the gas. The solution proposed is that in the event of any hydrogen leak occurring, the electrical supply to the overhead lines would automatically be cut. However, this would require highly responsive hydrogen leak sensors, reliable communications, and fast-acting circuit breakers. Ideally, reliable hydrogen sensors would also be needed in locations such as stations, maintenance depots, and storage sheds so that any leakage of hydrogen would be detected very quickly and steps taken to evacuate the area in question and increase ventilation.

Liquid hydrogen has a density that is nearly 850 times the density of hydrogen for standard conditions, and the use of hydrogen in liquid form is currently being considered for aircraft applications. It is possible that developments in that field could have implications for the railway industry in the longer term. There are many problem areas, including the cost of liquification and the need to ensure that the liquid hydrogen cannot evaporate and cause excessive pressures within storage tanks. Research on other storage methods is underway in many places, including the use of metal hydrides, liquid organic carriers, and porous nanomaterials.

In the specific field of design optimisation of hybrid powertrains involving hydrogen fuel cells and batteries, some potentially useful recent papers include those by Zhao et al. (2022) [63], by Liu et al. (2024) [64] and by Ding et al. (2025) [65].

A recent claim has been made that the cost of hydrogen refuelling stations has now fallen to a level of the order of €2M, which is equivalent to the cost of electrifying one kilometre of railway line. This was stated by a spokesman for the Lhyfe company, which is a producer of green hydrogen. [66].

4.2 Developments in hydrogen and fuel cell technology for railway applications in the United Kingdom

There is continuing interest in the UK in the possible use of hydrogen for passenger and freight train applications. This section is intended to highlight some developments that are considered particularly important. More details of recent developments in this field in the UK may be found in Appendix C. However, this report does not provide a comprehensive list of all UK projects.

One important continuing development project in the United Kingdom involving passenger trains is the *HydroFLEX* demonstration project, which involves collaboration between Porterbrook and the University of Birmingham's Birmingham Centre for Railway Research and Education (BCRRE) [67]. Some details relating to the design and performance of the train are provided by Calvert et al. [68]. A further publication involving authors from the BCRRE considers more general issues of hydrogen storage within rail vehicles [69], which is one of the important issues for trains in the UK, due to loading gauge limitations.

Another project involves a proof-of-concept vehicle based on a former Class 08 diesel-electric shunting locomotive. This is being developed by Vanguard Sustainable Transport Solutions, which is a spinout company from the BCRRE. A proof-of-concept vehicle was unveiled early in 2023, which is based on a former Class 08 diesel-electric shunting locomotive [70]. The locomotive was on display at the "Greatest Gathering" railway event that took place in Derby in August 2025.

In a very different type of development, Steamology, a UK-based company in Salisbury, has developed steam generator units powered by hydrogen and oxygen. A joint venture between Innovate UK, Eversholt Leasing, Steamology, Arup, and Freightliner has been established that involves rebuilding a Class 60 diesel-electric locomotive with 20 of these hydrogen-burning steam generators in place of the diesel engine. The aim is to assess the practicality of this technology for short-haul rail freight workings [71].

4.3 Developments in hydrogen and fuel cell technology for railway applications in Europe and elsewhere

In the years since the earlier reports [1], [2] were produced, there has been much progress (as well as some setbacks) in railway applications of hydrogen in Europe and in other parts of the world. This section provides a brief account of some of these developments. More details, together with examples of other developments in hydrogen-powered rail vehicles in Europe and elsewhere, may be found in Appendix D of this report.

As discussed in Section 4.1, the FCH$_2$RAIL project has provided a considerable amount of detailed information about experience gained with the design, development, building, and testing of a multi-purpose fuel cell hybrid powerpack, including the demonstration of its use in a multiple-unit train [54].

One interesting event that took place recently in France was the reopening, in June 2025, of the 36km Bagnères-de-Luchon branch on the Toulouse-Tarbes line. The Occitanie region owns the line and has paid for modernisation. Plans involve using the route as a shop window for the operation of hydrogen-powered trains, but services are currently operated using *Régiolis* bi-mode electric/diesel multiple units. These operate in diesel mode on the branch [72].

By December 2024, there were three hydrogen train fleets in service in Germany, but significant problems were being reported, both with the reliability of some trains and with the supplies of hydrogen. However, despite this adverse publicity, Siemens Mobility and its Smart Train Lease subsidiary have signed a cooperation agreement with Tyczka Hydrogen (a company based in München) that allows Smart Train Lease to offer, as part of its portfolio, fuel-cell trains with a full supply chain and appropriate support services based entirely on green hydrogen. [73].

Talgo announced, in January 2024, that the company would lead a consortium of ten Spanish firms in a project, named *Hympulso*, aimed at the development of a high-speed hybrid hydrogen/battery electric train. The new train would be used on long-distance services. It is intended that the batteries should be charged through reversible converters while the train is underway [74].

A Bo-Bo hydrogen centre-cab PEM fuel-cell locomotive has been developed by Polish manufacturer PESA, and this was showcased, both at TRAKO in 2021 and at Innotrans in Berlin in September 2022. Poland's Office of Rail Transport (UTK) granted authorisation in June 2023 to operate the locomotive on the national rail network. Apparently, this is the first hydrogen-powered locomotive in the world to receive this type of authorisation [75].

A different type of development is planned in Ireland, where Irish Rail (IE) has awarded a contract to a Latvian firm, DIGAS, to modify a General Motors-built diesel-electric locomotive to use hydrogen within its internal combustion engine using a DIGAS Hydrogen Internal Combustion Engine retrofit kit. Following conversion, IE plans to undertake an extensive programme of testing of the modified locomotive [76].

A hydrogen fuel-cell tram is being developed in Germany by a consortium called HyTraGen (Hydrogen-Tram for next Generation). It is hoped that the vehicle will be available for testing on the Gőrlitz network from December 2026. [77].

In China, developments have been particularly rapid. In 2013, the first fuel-cell locomotive in China was developed at Southwest Jiatong University. This involved a 150kW fuel cell stack and two 120kW permanent magnet synchronous traction motors to produce a continuous traction force of 20kN and a maximum design speed of 65km/h. This was followed in 2015 by the development by the CRRC Qingdao Safang Company of the world's first commercial hydrogen fuel cell tram. This was intended for operation on the Foshan tramway in Guangdong Province. At the opposite end of the power range, in 2021, CRRC and Tongji University produced the world's first megawatt-level hybrid hydrogen/battery-electric powered locomotive. The first commercially operated hydrogen-powered freight locomotive in China began trial runs in May 2025. That locomotive is intended for the short-haul transport of coal and forms part of a larger "Coal-Coke-Hydrogen" demonstration project [78].

The Foshan Hydrogen Tram line in Guangdong Province opened in 2019. Ballard Power Systems was responsible, along with CRRC, for fuel-cell system design, which involved two 200kW cells per tram. However, by early 2024, operations on the Foshan tram line had been suspended [79]. Hyundai Rotem in South Korea has since announced that the company is working on a new generation of hydrogen fuel cell trams [80], so there is still some optimism in East Asia about the future of hydrogen for light rail applications.

In the USA, San Bernardino County Transport Authority (SBCTA) signed a contract in 2019 with Stadler for the purchase of Flirt H2 trains [81]. This was the first development of hydrogen-powered trains in the passenger sector in the USA. Apart from those developments in California, relatively little interest appears to have been shown in hydrogen for railway applications, although there have been some theoretical studies (e.g. [82] - [83]) and one involving the Wabtec Corporation [84]. An interesting report by Khan and Shao [85], published in 2024, provides more details of this latter project, which involves collaboration between Wabtec and the Argonne and Oak Ridge National laboratories under a grant from the US Department of Energy. The aim of the work is to investigate how much hydrogen can be blended with diesel fuel to maintain diesel-like performance while reducing emissions of greenhouse gases and particulates.

Options involving hydrogen fuel cells and batteries for heavy-haul operations in Australia have been investigated in simulation studies carried out at the University of Queensland, where it was concluded that mass and space limitations for batteries severely constrain the operating range of battery-powered locomotives, as reported in papers by Knibbe et al. [86] and by Cole et al. [87]. In the case of hydrogen, although storage and related equipment occupy much space and containment systems for hydrogen-based systems tend to add significantly to the mass, the overall space and mass requirements could be as little as half those of purely battery-based systems. The use of higher-pressure systems for hydrogen storage would increase the maximum range, and the use of cryogenic storage could increase the range even further.

In Japan, in 2020, the East Japan Railway Co., in collaboration with Toyota Motor Corp. and Hitachi, conducted tests on the Hybari hydrogen-powered train, and in South Korea, Hyundai Rotem entered into a collaboration with Hyundai Motors to develop a hydrogen tram. In 2024, Daejeon City Government signed a contract for 34 of these vehicles for use on the Daejeon light rail network.

5. Recent developments in other types of short-term energy storage systems

In all forms of transport, recovery of braking energy helps to reduce energy usage and emissions. As pointed out in [2], this is not a new concept, and regenerative braking and subsequent energy storage and recovery are relatively straightforward for electrified railways and tramways using batteries or supercapacitors. However, in recent years, interest has grown in the possibilities offered by other approaches, including the development of superconducting magnetic energy storage systems and the further development of mechanical methods based on flywheels or hydraulic systems.

5.1 Superconducting magnetic energy storage for railway applications

Superconducting magnetic energy storage systems use superconducting coils with very low electrical resistance to produce very strong magnetic fields that allow the storage of large amounts of electrical energy for long periods of time. At present, applications are expected mainly within electrical power generation and distribution systems, but possibilities are also being seen for the use of this technology in regenerative braking systems for trains, especially if high-temperature superconductors and liquid nitrogen (rather than liquid hydrogen) could be used as a coolant. However, problems associated with large magnetic forces generated by the circulating coil currents are likely to limit this technology to lineside applications (see, e.g., [4]). Many research papers have been published in recent years concerning superconducting magnetic energy storage systems (e.g. [88] - [91]), but an obvious problem with this technology is that the capital, operational and maintenance costs of the necessary refrigeration systems are high, and the costs of liquefaction are significant. This means that superconducting storage is not seen widely as an attractive option at present. However, the current interest being shown in cryogenic fuels for aircraft suggests that liquefaction costs should decrease. Shen et al. published a conference paper in 2023 dealing specifically with railway applications [92].

5.2 Flywheel energy storage systems for railway applications

Papers by Li and Palazzolo [93], Xu et al. [94] and Choudhury [95] provide relatively recent accounts of the state of the art and possible future developments in flywheel technology. For railway applications, static lineside flywheel storage systems are well-established. They help to regulate the line voltage, improve the acceleration of electric trains, and allow energy to be recovered through regenerative braking. Useful accounts are provided by Jackiewicz [96] and by Khodaparastan [97]. Examples can be found in Japan, and in South Korea, and a section of line with flywheels in seven substations has produced a significant reduction in peak power demand and also cost-associated savings.

Flywheels have also been used on rail vehicles, one notable example being the Parry People Mover system on the Class 139 railcars used on the Stourbridge branch in the West Midlands of England. The review of railway applications of energy storage systems by Dominguez et al. [7], published in 2025, provides useful information about the experience gained from applications of this form of storage system. In modern flywheels, the rotors are made of high-strength carbon-fibre composites, suspended by magnetic bearings, and spinning at speeds from 20,000 to over 50,000 rpm in a vacuum. Such systems can reach their full energy capacity more quickly than some other forms of storage. Although flywheels offer high power density, their energy density is relatively low, and significant standby losses can occur, resulting in higher discharge levels compared to other forms of energy storage. Maintenance is relatively easy, but safety issues and the added mass associated with the provision of adequate rotor containment make this technology less attractive than other forms of on-board energy storage.

The technology firm Artemis Intelligent Power was reported in [2] to be working with Ricardo and Bombardier on a project entitled "Digital Displacement® Rail Transmission with Flywheel Energy Storage". This is a form of regenerative braking based on the Artemis system of Digital Displacement pump-motors. The novelty lay in its application to diesel trains with mechanical transmissions and by 2020, Artemis had demonstrated that the technology could lead to significant fuel savings and provide environmental benefits. For example, during a seven-month in-service trial on a ScotRail Class 170 diesel multiple unit, an annual fuel saving of 6.7% was identified. A project funded by the UK Rail Safety and Standards Board (RSSB) to investigate the possible use of Digital Displacement technology for traction and auxiliary power on small locomotives and track maintenance vehicles suggested that there were potential fuel savings to be made of up to 30%, depending on the duty cycle [98]. These findings are seen as pointing to a potentially valuable development for the rail freight sector. Artemis Intelligent Power Ltd. was taken over by Danfoss in 2021.

6. Recent developments in design methods for hybrid powertrain systems for railway applications

The design and optimisation of powertrain systems involving multiple power sources is inevitably complex. It is a field in which much experience has been gained from road vehicle design. Computer-based modelling and simulation techniques and related computational tools for system optimisation have an important role and are now being used routinely for applications involving rail vehicles. For example, the characteristics of hydrogen fuel cells mean that there are potential advantages in using them together with batteries or supercapacitors to form a hybrid system, as discussed in [2], but the design of the powertrain to provide the most effective use of these two power sources is not a simple task.

One approach that was used in a hydrogen train project funded by Scottish Enterprise and Transport Scotland, and discussed in Appendix C, involved the application of inverse simulation methods [99]-[101]. This approach allows the required output power at the rail to be found for a hybrid train design to match the performance of an equivalent diesel train for a specific route in terms of its speed versus time or distance travelled versus time profile. Simulation methods then allow insight to be gained regarding the best use of energy from the fuel cell and the battery. Hydrogen fuel cells have dynamic characteristics that are sluggish, and they are normally used together with batteries and short-term energy storage devices, such as supercapacitors, to provide rapid responses to sudden changes in demanded power and also to allow regenerative braking. Techniques involving multi-objective optimisation tools are potentially very important in investigating design problems of this kind involving two or more energy sources (e.g., [102]). In addition to considering sizing issues for fuel cells, batteries, and supercapacitors, such systems raise additional energy management and control system design issues. There are many relevant reports and papers, including a paper by Deng et al [103] on eco-driving and energy management in hybrid powered trains, and a paper by Kepetanović et al. [104] that considers an internal combustion engine or fuel cell as the main source of motive power, in conjunction with other forms of energy storage such as lithium-ion batteries or supercapacitors. On the topic of freight train applications, there is an interesting account by Zhang et al. [105] of the application of particle swarm optimisation methods in a simulation study aimed at minimising operating costs while determining appropriate component sizes for freight trains powered by solid oxide fuel cells using either hydrogen or ammonia. The findings suggest that the use of ammonia could reduce costs significantly compared with the use of hydrogen, but more space would be required.

Developments in the aircraft industry are also very relevant for railway applications. Although successful experimental tests of aircraft using hydrogen as a fuel have already taken place, issues of fuel-cell volume, weight, and efficiency, battery weight and volume, and provision of an appropriate hydrogen infrastructure are even more important in that field than in the rail industry. A very recent paper by Cäsar et al. [106] provides interesting information about some developments in the aircraft industry.

7. Discussion

Much of the discussion in the earlier reports [1], [2] remains relevant today. Notable developments that have taken place during the five years since those reports were prepared include the growing attention being given to discontinuous electrification and the use of batteries to provide power over route sections that are not electrified. Clearly, much remains to be done in terms of the transition from diesel traction to other, more environmentally-friendly, types of motive power, and it is important that those working within the rail sector should keep themselves fully aware of relevant developments. It is hoped that this report provides some useful information in that respect.

Since the year 2020, when the earlier reports were completed, there has been a growing acceptance that the emphasis on decarbonisation of passenger rail transport could result in lost opportunities in terms of rail freight services. Although discontinuous electrification may provide satisfactory solutions for passenger services in some cases, this is of very limited value for freight, as battery technology does not appear viable for that application. Bi-mode configurations based on batteries may be useful for freight locomotives for "last mile" and other very short sections of non-electrified track. However, the added mass of batteries needed to provide traction power for freight services and other locomotive-hauled trains over the gaps proposed in discontinuous electrification schemes is currently unacceptable, leading to increased power requirements overall and significant additional costs. Hydrogen fuel cell technology might, in the long term, provide solutions, but this is at an early stage of development for rail freight, as outlined in Section 4 and in the appendices.

Hybrid approaches involving multiple energy storage devices, such as batteries and supercapacitors, allow active and potentially optimal sharing of power. As discussed elsewhere in this report, supercapacitors provide higher power densities than batteries but have lower energy densities. As a result, they can provide a large current for a short period of time, reducing the burden on the battery and thus extending its life. In addition, unlike batteries, supercapacitors allow deep discharges to occur in terms of the state of charge without damage. It is important to establish the possible future roles of these storage devices in heavy rail and tramway operations.

Hydrogen fuel cell technology is still at an early stage, and one of the main reasons for this is the cost of providing the necessary infrastructure for the production, distribution, and storage of hydrogen. Other methods of production are the subject of research and development projects, some using domestic waste or discarded plastic, but these have not yet been applied on a large scale. It is important that progress with developments of that kind continue to be reviewed regularly.

Powertrains that use batteries in conjunction with hydrogen fuel cells and supercapacitors involve other complex sub-systems such as electric motors, power electronic inverters and DC/DC converters. Developments continue to be made in the engineering aspects of these sub-systems, and optimisation of the complete system involves complex engineering design decisions that have a bearing on performance and have direct effects on capital and maintenance costs. Modern design optimisation methods have much to offer in terms of railway applications, and the growing attention being given to discontinuous electrification is important for overall system design optimisation, which can now include the siting of electrified sections of route.

8. Conclusions

As was stated in [2], many factors affect the choice of powertrain elements for a specific transport application. Trends in recent years show falling manufacturing costs and significant performance improvements for batteries, supercapacitors and hydrogen fuel cells, but the geopolitical uncertainties mentioned previously [1], [2] concerning the supply of some raw materials required for the manufacture of these components and for modern forms of electric motors remain important.

Areas of research that are particularly relevant for future applications in heavy rail and light rail systems include new chemistries that are extending the range and lifespan of batteries, supercapacitors and fuel cells. Developments in electrolysers for more efficient and less costly production of hydrogen for fuel cells are also of great interest, as are developments in the storage of hydrogen and its transportation. Other forms of short-term energy storage are important for the rail industry, and developments in flywheel systems and hydraulic energy storage systems continue to be of interest. Even more relevant is the rapid build-up of practical experience in the manufacture, testing, operation and maintenance of battery and hybrid trains.

The growing attention being given to intermittent electrification in many countries is a significant factor. However, intermittent electrification should not be seen as a long-term alternative to conventional electrification of a complete route, as it is unlikely to meet the needs of freight and other locomotive-hauled services in the near future. Bi-mode or tri-mode hybrid powertrain configurations involving combinations of electric traction, hydrogen fuel cells, battery-electric and possibly internal combustion engines could all have a role for locomotive-hauled trains.

It is likely that research and development work currently underway on the fundamentals of powertrain systems and energy storage will lead to important steps forward, and it is important that the rail industry should be at the forefront in terms of applying these new developments. This requires close links to be maintained between manufacturing companies, train leasing companies, rail infrastructure organisations and train operators so that the industry can move forward. Maintaining good links between these organisations and counterparts in other industrial sectors, as well as those involved in more fundamental research, such as in universities and government research institutes, is also vitally important. For example, experience now being gained in the bus and truck industry with vehicle powertrains based on batteries and fuel cells is likely to be of immediate relevance for rail transport, as are developments in the aircraft industry.

In summary, much progress and some setbacks have occurred in this field since 2020, when the earlier reports were produced. Much practical experience has been accumulated, and some new problems have been identified, especially in terms of regulations for the operation of trains involving novel forms of powertrains or energy storage systems. All involved in this field need to recognise the significance of new developments across the world and take full account of those in attempting to move forward in their own fields.

Appendix A

Details of recent developments in battery-electric train technology in the United Kingdom.

A1 Discontinuous electrification in the UK

In terms of modern developments aimed at routes with intermittent electrification where gaps exist in the overhead catenary or third rail, Siemens Mobility has announced that bi-mode battery-electric trains could be produced in the future at its factory in Goole. Fitted with lithium titanate oxide (LTO) batteries, it is claimed that these trains would require installation of catenary on only 20-30% of a discontinuously electrified line [107]. The company is linking this to the use of its Rail Charging Converter (RCC) hardware [29], as outlined in Section 2.2 and discussed further in subsection A2 below.

Another significant development in the plans for intermittent electrification schemes has involved tests of a Transpennine Express (TPE) Class 802/2 Hitachi unit with a high-energy battery in place of one of its three diesel engines. This is a collaborative project involving TPE, Hitachi, battery manufacturer Turntide Technologies and Angel Trains, which owns the Class 802/2 set. These trials were intended to provide data to support a business case for a battery and electrically-powered inter-city train capable of running 60 miles in battery mode. It is likely that the trials were successful, as it has been announced recently that Turntide Technologies will supply second-generation lithium-iron-phosphate (LFP) batteries for nine Hitachi tri-mode trains that are being built for the open-access operator Grand Central [108]. These batteries are claimed to be smaller and more powerful than conventional lithium-ion batteries.

In a similar development, involving a different manufacturer, LNER has ordered a fleet of ten new 10-car tri-mode trains from CAF, financed by Porterbrook [109]. These will be the first tri-mode inter-city trains in the UK and are based on the CAF *Civity* train design. They will be capable of operating in electric, diesel, and battery electric modes and will be assembled in Newport, South Wales. The battery can recharge in both electric and diesel modes, and the train can be operated both in battery-only mode and with a combination of diesel and battery power.

As discussed in Section 2.2, Stadler has provided bi-mode electric/battery-electric Class 777/1 trains for the 0.83-mile non-electrified Merseyrail route to Headbolt Lane. The additional weight of the batteries is approximately 5 tonnes. This was part of an order for 53 Class 777s from Stadler by Liverpool City Region Combined Authority (LCRCA). These bi-mode units are referred to as Independently Powered EMUs (IPEMUs). Although it has been reported that there were some reliability problems with these units initially, it appears that the batteries themselves have performed well. The range under battery power is estimated to be between 50 and 70km, with a 15-minute charging time [24]. Stadler is also supplying *Class 756 mAF* battery-electric/diesel trains for Transport for Wales [25].

More operators are showing interest in BEMUs, as mentioned in Section 2.2. For example, Chiltern Railways published tender notices in September 2022 for BEMUs with an estimated contract start date in January 2025 [26], and in July 2025, a market engagement notice was published by ScotRail for the procurement of around 41 new electric multiple unit trains and 28 BEMUs. Initial unit deliveries are expected to begin in late 2030, subject to approval from Transport Scotland and the Scottish Government. This would coincide with the completion by Network Rail of the partial electrification of some routes that are not electrified at present, probably involving lines in Fife serving Dunfermline, Kirkcaldy, and Levenmouth [27].

A2 Battery train experience and developments in fast-charge systems in the UK.

In 2018, Vivarail successfully demonstrated a two-car battery-powered Class 230 unit based on the "D-Train" that the company had created by rebuilding redundant London Underground District Line stock originally introduced in 1980. One of those demonstrations took place on the Bo'ness and Kinneil Railway in Scotland in October 2018 (Figures 1 and 2). A three-car version of this Class 230 unit was also demonstrated in Scotland during the COP26 event in Glasgow in the autumn of 2021 (Figure 3).

Figure 1. Vivarail Class 230 No. 230002 at Manuel station during a demonstration run on the Bo'ness and Kinneil Railway for invited guests of Vivarail.
Photograph: David Murray-Smith, 11/10/2018

Figure 2. Vivarail Class 230 No. 230002 at Bo’ness station following the demonstration run.
Photograph: David Murray-Smith, 11/10/2018

Although the Vivarail company went into administration in November 2022, its assets, in the form of rolling stock and intellectual property associated with the development of Vivarail Fast Charge technology and high-performance battery systems, were purchased by the train operating company Great Western Railway (GWR). This allowed the development work to continue, and the three-car unit No. 230001 was tested extensively on the 2.5-mile-long branch line between West Ealing and Greenford for about one year, ending in July 2025. Results suggest that fast-charge battery trains could be a viable option for GWR for branch lines currently operated by that company in the Thames Valley, Devon, and Cornwall. The overall efficiency claimed is 79%, with a power consumption of approximately 2.4 kWh/vehicle/mile, which is reportedly better than that of a diesel-powered train on an equivalent duty [28]. GWR is working with the Department for Transport (DFT) on proposals for new trains to replace the existing regional fleet of DMUs, and recommendations are expected to involve discontinuous electrification with on-board energy storage using batteries and charging points at stabling facilities [110].

Figure 3. Vivarail Class 230 No. 230001 at Glasgow Central Station in November 2021 before a demonstration run to Barrhead for COP26 delegates and guests invited by Vivarail. (Photograph: David Murray-Smith, 09/11/2021)

The Vivarail fast charge system uses trackside battery banks, which are trickle-fed continuously from the national grid through a connection similar to a domestic supply, but can be configured to use off-peak energy only or to export to the grid.

As mentioned in Section 2.2, and Appendix A1, Siemens Mobility has launched its new Rail Charging Converter (RCC) in a development that received funding from Innovate UK and Porterbrook. It is claimed that the RCC can fully charge a train in twenty minutes and is ideal for discontinuous electrification schemes [29]. Inverness to Wick and Thurso could be considered an extreme case for discontinuous electrification, and it has been suggested that two 15-mile recharging sections of overhead electrification might be sufficient on that route using RCC equipment. Siemens Mobility's preferred option in terms of battery chemistry involves Lithium Titanate Oxide (LTO) batteries [111].

A3 Developments in battery-powered locomotives in the UK

Clayton Equipment of Burton-on-Trent received an order for fifteen 90-tonne shunting diesel-electric locomotives in 2020, and the first locomotives were expected to be handed over to customers early in 2024. Designated as Class 18 locomotives, they are equipped with Stage V emissions-compliant JCB diesel engines but can also be operated solely on battery power. Recharging is possible through regenerative braking, plugging in to a suitable supply, or from the diesel power unit [112].

Meteor Power at Silverstone in the UK has been working on the conversion of a Class 08 diesel-electric shunter (No. 08649) to incorporate a hybrid powertrain involving a 300kW battery pack and a 225kW John Deere engine that can be used to move the locomotive in an emergency but is not intended to serve as the main form of propulsion. The maximum speed of the locomotive remains 20mph, but the maximum tractive effort has been increased by about 28%. The converted locomotive will be fully Network Rail-compliant and, after trials on the Great Central Railway, it is intended that the locomotive will go on hire to Tarmac at Tunstead. It was expected that the locomotive would also have a trial period with Freightliner. The original English Electric traction motors are being retained, along with the bodyshell and cab. Test results suggest that CO2 emissions are 87% lower than in the original design [113].

Another interesting recent development is the prototype Class08e locomotive designed and developed by Positive Traction (PT) in conjunction with a sister company (RMS Locotec), which provides shunting locomotives on hire. The existing diesel engine in a Class 08 diesel-electric shunting locomotive was replaced with lithium-ferro-phosphate (LFP) batteries contained within a PT "Powerpod". Each pod, which has charging equipment and a battery management system, has a rating of 88kWh and there is space for six pods within the locomotive. The Powerpods are supplied by Lithion, which is the company supplying batteries for the Vivarail unit. Tests have been carried out at a number of sites in the UK, including Whatley Quarry in Somerset, where the locomotive successfully moved 1000-tonne aggregate trains. The first production Class 08e is now under construction and will be delivered to Whatley Quarry for testing in the near future [114].

A4 Developments in light rail applications in the UK

In terms of practical moves towards the use of batteries on tramways and light rail systems, one notable development in the UK is the project for Very Light Rail (VLR) being undertaken in Coventry [30]. A prototype battery-powered vehicle manufactured in Coventry by NP

Aerospace began trial running on a special section of test track in Coventry city centre in 2025. A three-week programme of public demonstrations ended in June 2025. The vehicle, which weighs 11 tonnes unladen and 16 tonnes fully laden with up to 72 passengers has lithium titanate oxide (LTO) batteries providing 50kWh of energy and a theoretical range of 50-70km depending on vehicle load and air temperature. It will undergo further testing at the Very Light Rail National Innovation Centre in Dudley before returning to an 800 metre long demonstration line in Coventry city centre in 2027. The VLR vehicle can be charged from 10% to 90% in 12 minutes using a 450kW charger designed for buses, which utilises a pantograph lowered from above [115].

The currently disused Heathfield branch line from Newton Abbot in Devon, which last saw passenger trains in 1959, has been the subject of a study by Lampitt Rail, commissioned by Eversholt Rail. This train leasing company and its manufacturing partner, Transport Design International, stated in 2023 that they planned to build three new *Revolution* battery-powered vehicles intended for lightly used routes. Operational tests and passenger trials are planned, and the first vehicle should be available for testing in 2026 [116].

Appendix B

Details of developments in battery-electric train technology in other parts of Europe and elsewhere.

As pointed out in Section 2.3, the situation in terms of the introduction of battery-electric trains in other parts of Europe is somewhat different from that in the United Kingdom. For example, in Germany, several manufacturers already have battery-electric trains in service or are expected to have their products introduced in the near future, including the Stadler *Flirt Akku* units in the state of Schleswig-Holstein. These started operation between Kiel and Kiel Oppendorf in October 2023 [31]. To allow BEMUs to operate on lines that are not electrified, three “electrification islands” are now being created through small extensions of existing electrified infrastructure and electrification of station platforms (at Heide and Husum on the Hamburg to Westerland route and at Tōnning on the branch to Bad St. Peter Ording). The trains are designed to operate for up to 150km between charges, but normal operation will involve only 80km. Also, twenty Siemens *Mireo Smart Plus B* Class 536 BEMUs were expected to enter service on regional routes in the Black Forest area in December 2024, with a further thirty-one units on order in January 2024 for services in Brandenburg near Berlin [32]. These are electric/battery-electric multiple unit trains, which have a range of up to 120 km and a top speed of 140 km/h (both in battery mode and when supplied from overhead lines). On routes with discontinuous electrification, the batteries can be charged through the pantograph while in motion.

Eleven Alstom *Coradia Continental* BEMUs were expected to appear on services between Leipzig and Chemnitz in 2024. CAF is building a fleet of 73 *Civity* BEMUs for use in the Ruhr region, and additional orders have been placed for Stadler *Flirt Akku* BEMUs for operation in Germany from 2025-26. As in Schleswig-Holstein, to allow BEMUs to operate further from the electrified network in Sachsen, an overhead electrified “island” and smart charging station have been built at Annaberg-Buchholz Süd station. This site hosts the Smart Rail Connectivity Campus which is run in conjunction with the Technical University of Chemnitz.

As discussed in Section 2.3, Siemens *Mireo Smart Plus B* battery-electric multiple unit trains received authorisation to operate on the Danish rail network and entered service with limited passenger operation on the Vemb-Lemvig-Thyborøn route in July 2025. Until then, all services were operated by Siemens *Desiro Classic* diesel multiple units along with lightweight *Y-tog* diesel multiple units, the earliest examples of which were built in the mid-1960s. Work is still underway on charging stations for the routes on which the new units will operate.[33]. Sjælland regional council in Denmark is investing in Stadler *Flirt Akku* BEMUs for Lokaltog for use between Holbæk and Nykøbing Sjælland. That line meets the Tølløsebanen at Holbæk, and with BEMUs also operating on the Tølløsebanen between Tølløse and Slagelse, this enhances the operating flexibility of the BEMUs [34].

A battery hybrid version of the *Régiolis* multiple unit entered service on the Toulouse-Castres-Mazamet route in France. This was previously a bi-mode overhead electric/diesel unit, and two of the four roof-mounted diesel engine packs have been replaced by battery packs. Regenerative braking allows 90% of braking energy to be recovered, and energy consumption is reduced by 20%. Most of the line to Mazamet is not electrified, and it is assumed that the battery packs will boost the power from the diesel engines [35].

Trenitalia has launched an inter-city version of the Hitachi *"Blues"* Class HTR412 train on the route from Tarantalabria to Reggio di Calabria in Italy. These are four-mode hybrid trains with diesel engines, overhead electric power via a pantograph, and on-board batteries. The fourth mode involves using diesel engines and batteries together. The maximum speed is 160km/h when operating as an EMU and 140km/h in other modes [36].

Details of the Czech Railways (ČD) order placed in mid-2024 for fifteen *RegioPanter* 1360kW BEMUs from the Škoda Group, include the fact that the units will have a maximum speed of 160km/h in overhead electric mode and 120Km/h in battery mode [37].

In Ireland, the Dublin Area Rapid Transit (DART) network ordered thirteen 5-car BEMU sets from Alstom in December 2021 to allow operations beyond the limits of the currently electrified network [38]. Within the electrified network, the trains will operate in purely electrical mode. It is hoped to have the first trains in service by the end of 2025. A further order for eighteen 5-car BEMUs was placed in December 2022. Roof-mounted lithium-ion batteries are used and have water cooling. They are mounted at the outer ends of both driving vehicles. The total energy storage capacity is 840kWh with a predicted range of 80km. Charging is only possible at charging points, and it is not possible to charge from the catenary [117]. The first unit was due to be shipped from Alstom's Katowice factory in September 2024 (with batteries shipped separately) for final assembly, testing, and commissioning at Inchicore Works in Ireland [118].

In December 2023, Vossloh Rolling Stock presented the first DE 18 Smart Hybrid locomotive to the press and customers at the Imateq depot at St. Pierre-des-Corps near Tours in France. This is one of 30 to be delivered to the Nexrail leasing company. Diesel engines are retained, but two 1000 litre auxiliary fuel tanks have been replaced by Kiepe battery packs. These batteries allow about one hour of operation at up to 40km/h on battery power alone. Charging is possible by the diesel engine or by plug-in, but not using regenerative braking energy [39].

Vossloh Rolling Stock is also planning to convert a G1000 diesel-hydraulic locomotive into a diesel/battery hybrid known as G1000 Neo. The work will involve removing the diesel engine and gearbox, installing a 300kW generator and traction motors, plus batteries to provide 480 kW of power [39].

There are now many examples of battery use on tramways and light rail systems worldwide, especially where there are areas of cities where it is thought that the addition of catenary would be detrimental in terms of the historic environment. In Granada, for example, the tram fleet, which is based on CAF *Urbos 3* trams, is equipped with CAF's ACR system for fast-charging of roof-mounted supercapacitors required for several wire-free sections of line [119].

Appendix C

Details of recent developments in the use of hydrogen for railway applications in the United Kingdom.

The most important continuing project in the United Kingdom involves the Porterbrook 'HydroFLEX' demonstration project, which is based on a former Class 319 electric multiple unit, as shown in Figure 4. This work involves collaboration between Porterbrook and the University of Birmingham's Birmingham Centre for Railway Research and Education (BCRRE) [67]-[69].

Figure 4. The Porterbrook/BCRRE Class 319 electric multiple unit which has been converted for hybrid fuel cell/battery operation. This view shows the unit at Glasgow Central Station before a demonstration run to Barrhead using electric traction only for COP26 delegates and invited guests.
(Photograph: David Murray-Smith, 09/11/2021)

Early in 2020, Transport Scotland and Scottish Enterprise announced support for the development of a hydrogen fuel-cell/battery-electric multiple unit (HFCBEMU) for trials in Scotland, with the Hydrogen Accelerator group at the University of St Andrews involved in managing the project [120]-[122]. A contract for converting a former ScotRail Class 314 three-coach electric multiple unit (Figures 5-9) to a hybrid configuration was awarded in December 2020 to a consortium of companies led by Arcola Energy Ltd, which later became Ballard Motive Solutions. The other member companies were Arup, Abbot Risk Consulting (ARC), AEGIS and Angel Trains.

Design work on the hydrogen train was carried out by engineers from Ballard and from within the consortium, with conversion of the Class 314 to the hybrid unit (Classified as Class 614) being carried out at the workshops of the Bo'ness and Kinneil Railway. A hydrogen electrolyser unit and refuelling facilities were installed at Bo'ness station. The train and the electrolyser unit were displayed at Bo'ness during the COP26 event. Successful trials of the converted train took place on the Bo'ness and Kinneil Railway between Bo'ness station and Birkhill station during 2022, and the project was concluded later that year. The electrolyser unit has since been moved from Bo'ness to the University of St Andrews, and the train (without the hybrid powertrain units) is now used for employee training at the Springburn workshops of Gibson's Engineering in Glasgow.

Figure 5 . Hybrid FCBEMU 614209 at Bo'ness station.
Photograph: David Murray-Smith, 08/11/2021

Figure 6. Platform view of No. 614209 at Bo'ness showing consortium partner logos.
Photograph: David Murray-Smith, 08/11/2021

Figure 7. The interior of one coach of the hybrid multiple unit No. 614209.
Photograph: David Murray-Smith, 08/11/2021

Figure 8. Hydrogen cylinders forming part of the facilities for refuelling at Bo'ness station.
Photograph: David Murray-Smith, 08/11/2021

Figure 9. Electrolyser and refuelling equipment at Bo'ness station.
Photograph: David Murray-Smith, 08/11/2021

During 2021 and early 2022, some collaboration took place between engineers at Arcola Energy and members of staff at the University of Glasgow, together with a postgraduate student. The work focused particularly on the use of inverse simulation methods for hybrid powertrain design [99]-[101], [123]. This collaboration also highlighted more general problems concerning the modelling and simulation of train longitudinal dynamics and the effects of track curvature and gradients, leading to further research that is still underway. The collaboration also led to further work being undertaken at the University of Glasgow concerning applications of fuel-cell technology to rail traction, and this is still progressing.

Early in 2023, Vanguard Sustainable Transport Solutions, which is a spinout company from the BCRRE, unveiled a proof-of-concept vehicle based on a former Class 08 diesel-electric shunting locomotive No 08635, which has been renumbered H3802. The project has involved replacing the diesel engine by a hybrid powertrain involving an 80kW Toyota fuel cell and a 230kW battery unit to give an overall tractive power output of 250kW. Initial testing of the locomotive involved purely electrical operation using lead-acid batteries [70]. The locomotive was on display at the "Greatest Gathering" event that took place in Derby in August 2025.

Although current applications of hydrogen fuel cells for freight locomotives in the UK have been limited to shunting locomotives, the new bi-mode Class 99 freight locomotives being supplied to GB Railfreight by Stadler could, in future, have the diesel engines replaced by a battery pack or hydrogen fuel cell, according to statements from the GB Railfreight Safety and Sustainability Director [124].

Although not concerned with a rail traction application, an interesting development by the Advanced Hydrogen Technologies Group (ATH) as part of the Clean Futures programme run by the Black Country Innovative Manufacturing Organisation. It concerns the use of hydrogen to reduce fuel consumption in a diesel engine and reduce emissions, and involves a collaboration between ATH and Harry Needle Railroad Company (HNRC). This is based upon an add-on system that combines carbon capture and hydrogen production. It has already been used in automotive applications and uses hydrogen to remove residual carbon that has built up in the diesel engine. This is done by fitting a hydrogen generator unit to the locomotive. It uses water and an electrolysis process to produce hydrogen, which is fed into the engine through the air intake. The hydrogen helps to dislodge the carbon build-up, which then leaves the engine through the exhaust or is caught by a carbon capture device, if fitted. An HNRC Class 08 shunting locomotive was used for testing over two weeks. In the first week of tests, a four-cell hydrogen generator was used to clean the engine, and the following week, a bespoke "capture" device was added to further reduce harmful emissions (including particulates). Published results show that exhaust gas emissions were reduced by 22% overall, and heavy particulates by 20%. The fuel saving amounted to 8%. Statements from AHT suggest that the system is available for commercialisation. [125].

In a development that is very different from others discussed here, Steamology, a UK-based company in Salisbury, has developed steam generator units powered by hydrogen and oxygen. A joint venture between Innovate UK, Eversholt Leasing, Steamology, Arup, and Freightliner has been established that involves rebuilding a Class 60 diesel-electric locomotive with 20 of these hydrogen-burning steam generators in place of the diesel engine, to assess the practicality of this technology for short-haul rail freight workings [71]. It is planned to retain the alternator, traction motors and associated electronic systems, with the steam being fed to four steam turbines to provide a maximum power output of 2 MW. On-board hydrogen storage tanks would have capacity for 140 kg of gas [126]. This project is named "New Dawn" and the conversion work was expected to start in 2025 [127].

Appendix D

Details of recent developments in hydrogen train technology in other parts of Europe and elsewhere.

As discussed in Section 4.1, the FCH_2RAIL project [54] has provided a considerable amount of information about experience gained with the design, development, building, and testing of a multi-purpose fuel cell hybrid powerpack, including the demonstration of its use in a bi-mode *Civia* multiple unit train. Possible barriers to the adoption of hydrogen-powered trains on European rail networks were investigated, and the competitiveness of fuel-cell traction was compared with existing diesel multiple units. The unit was powered from the catenary when operating over electrified sections and by fuel cells and batteries on non-electrified lines. Batteries had to be rechargeable from the overhead power lines. Authorisation was required to allow the train to be tested in three EU member states (Spain, Portugal, and Germany), and appropriate refuelling facilities had to be available in the relevant locations.

An existing CAF *Civia* three-coach electric multiple unit was converted to form a fuel-cell/battery electric hybrid unit, with two fuel-cell hybrid powerpacks being integrated into the original traction system. Testing of each of the powerpack sub-systems was started in November 2021 in a process that involved hardware-in-the-loop simulation, with testing of the complete system on a test bench in spring 2022. Stationary testing of the train fitted with one powerpack began in May of that year, with dynamic testing being carried out over the period July to September 2022. By February 2023, the train had been fitted with a second fuel-cell hybrid powerpack and began tests, initially over a closed section of line and then, in May 2023, on the Zaragoza to Canfranc line. which forms part of the Spanish National Network. Authorisation for operation more generally on the Network was given by ADIF in October 2023, and the train underwent 37 days of dynamic testing, covering 16,000 km in Spain and Portugal in total, from November 2023 to April 2024, with 10,000km in hydrogen mode. Results allowed the computer simulation of the train and powerpack to be tested under a wide range of conditions, and the computer-based model was judged to be fit for purpose. This allows it to be used for investigations of possible system modifications that could lead to performance improvements.

Six Toyota GEN2 fuel cells with a net power output of 80 kW each provided a total of 480 kW, but it was concluded that, although suitable for the demonstration project, the power level should be increased to provide higher power in any future developments. The pantograph could be used on routes with 3 kV DC catenary. The battery sub-system could provide a maximum power output of 1044 kW and had a storage capacity of 238 kWh. Hydrogen storage was at 350 bar, with a total storage capacity of 160 kg of hydrogen. Test results suggested that the unit could travel for more than 800 km in self-powered mode. However, the provision of facilities for high-capacity fast refuelling of hydrogen was identified as an area in which further development work was required, and more work is also required on heating, ventilation and air conditioning systems. Overall, it was concluded that the main objectives of the project were all met.

The earlier report to SAPT [2] included mention of the fact that, by 2019. Alstom *Coradia iLint* hybrid hydrogen/battery-electric trains were in service in Germany. By December 2024, there were three hydrogen train fleets in service in Germany, but significant problems were being reported, both with the reliability of some trains and the supplies of hydrogen. Alstom withdrew most of its fleet of *iLint* hydrogen multiple units used on services to the north of Frankfurt am Main (Figures 10 and 11) as the trains required repairs under warranty. It appears that Alstom now intends to carry out a complete overhaul of each train, although they are less than four years old. Some components of the hydrogen powertrain will be replaced, and larger hydrogen storage tanks will be installed to increase the time between refuelling operations and thus reduce the damaging effects of delays encountered in accessing hydrogen supplies. During 2024, problems were also reported with *iLint* trains in Lower Saxony (used on the Cuxhaven to Buxtehude line to the west of Bremen). These were also associated with difficulties in obtaining hydrogen supplies and the reliability of fuel cells.

Figure 10. An Alstom *iLint* unit at Frankfurt-am-Main. The BEMU No 554614 prepares to depart from the Hauptbahnhof on the 12.17 service to Kōnigstein (Taunus)
Photograph David Murray-Smith 12/09/2024

Figure 11. The external décor on the Alstom *iLint* BEMU No 554614, as seen in service at Frankfurt-am-Main Hauptbahnhof
Photograph David Murray-Smith 12/09/2024

Although hydrogen-powered trains have received much adverse publicity in Germany, Siemens Mobility and its Smart Train Lease subsidiary (as mentioned in Section 4.3) have signed a cooperation agreement with Tyczko Hydrogen (a company based in München) that allows Smart Train Lease to offer, as part of its portfolio, fuel-cell trains with a full supply chain and appropriate support services based entirely on green hydrogen [73]. The fuel cells in the *Mireo Plus H* trains are supplied by Ballard, as is the case for hydrogen trains manufactured by Stadler [128]. In December 2023, Arriva Nederland cancelled an order for four hydrogen-powered trains and the associated refuelling infrastructure [129].

The announcement by Talgo in January 2024, mentioned in Section 4.3, that the company would lead a consortium of Spanish companies in a project aimed at the development of a high-speed hybrid hydrogen/battery electric train involved incorporating a vehicle into a conventional variable gauge Talgo trainset. The maximum service speed would be 250km/h, and the vehicle would be equipped with hydrogen fuel cells, batteries, and hydrogen storage tanks. The new vehicle would replace vehicles currently providing diesel power on Class 730 Talgo trains in Spain and would be used on long-distance services, with the batteries being charged through reversible converters [74].

The Bo-Bo hydrogen centre-cab PEM fuel-cell locomotive developed by Polish manufacturer PESA and mentioned in Section 4.3 is equipped with four 180kW traction motors, two Ballard 85kW hydrogen fuel cells, and a 167.6 kWh lithium titanate oxide battery. The total stored hydrogen capacity on the locomotive is 175kg, and the maximum refuelling time is 30 minutes. The maximum design speed of this shunting locomotive is 90 km/h. During tests in Poland, a prototype locomotive hauled a 3200-tonne train on level track. In September 2023, it made the first passenger-carrying journey by a hydrogen-fuelled locomotive in Poland. Poland's Office of Rail Transport (UTK) granted authorisation in June 2023 to operate the locomotive on the national rail network [75]. Vista Rail in Sweden intends to lease 20 of these SM42 6Dn locomotives from Hankavik, with a prototype locomotive being displayed in Stockholm in May 2025. The first production locomotive for Vista Rail is expected to start operation in 2027 or 2028. PESA has started design work on a new *Loco 2H* shunting locomotive, which will be a bi-mode electric and hydrogen fuel-cell type. The prototype is expected to be ready in 2026 or 2027.

In another recent development, a prototype hydrogen shunting locomotive has been developed in Italy, by SITAV, based on the frame and bogies of an existing locomotive. It is claimed that this can pull 2200 tonnes on a 4% gradient. It was unveiled at the Hydrogen Expo in Pracenza, Italy, in 2025 [130].

As reported in Section 4.3, Irish Rail (IE) has placed a contract with a Latvian firm, DIGAS, for the modification of a diesel-electric locomotive to allow the use of hydrogen within its internal combustion engine using a retrofit kit [76].

A hydrogen fuel-cell tram is being developed in Germany by a consortium led by Hőrman Vehicle Engineering GmbH in Chemnitz in collaboration with light rail vehicle manufacturer HeiterBlick, technology company Flexiva Automation and Robotics and Chemnitz Technical University, as mentioned in Section 4.3. The cost of the project is €8M, and it is intended that the vehicle should be in use for testing on the Gőrlitz network by December 2026 [77].

In China, the first commercially operated hydrogen-powered locomotive began trial runs in May 2025 at Luipanshui, in Guizhou province, as outlined in Section 4.3. The locomotive has an 800 km range and is capable of hauling 4500 tonnes. The hybrid powertrain involves a lithium-ion battery. It is intended for the short-haul transport of coal. Refuelling time is 15 minutes. Hydrogen is sourced on-site as a by-product from a coke-oven gas plant. It is intended that a local network of hydrogen filling stations will refuel heavy trucks and buses as well as the locomotives. This forms part of a larger "Coal-Coke-Hydrogen" demonstration project in which the local government is partnered with Meijin Energy [78].

The Indian railway minister announced early in 2015 that India is developing a hydrogen fuel-cell locomotive with an output of 1200 horsepower. It is expected to undergo trials in Haryana on the Jind to Sonipat route. [131].

In South Korea, tenders were invited in the first half of 2025 for a new tram network in the city of Hwaseong involving two lines, involving a total route distance of 31.6 km. Both lines are to be catenary-free with either battery or hydrogen-powered vehicles. It is hoped that construction can start later in 2025 [132].

The Chinese company CRRC Qingdao Sifang produces hydrogen fuel cell trains and light rail vehicles. Examples of that company's products are a hydrogen train, which has a hybrid powertrain involving a combination of hydrogen fuel cells and batteries and the Foshan Hydrogen Tram line in Guangdong Province, China, which opened in 2019. Ballard Power Systems was responsible, along with CRRC, for fuel-cell system design involving two 200kW cells per tram. However, by early 2024, operations on the Foshan tram line had been suspended due, apparently, to weak passenger demand and rising costs [79].

Footnote. This review forms part of a more extensive study of public transport energy costs and emissions in the context of developments in power sources and energy storage methods. The review is based on results from a continuing project that began in May 2018. Links shown in the reference list were successfully accessed during October 2025, but the continuing availability of the relevant sources cannot be guaranteed. The author wishes to acknowledge support and assistance from members of the Scottish Association for Public Transport (SAPT) who have provided useful information about reports, articles and news items for this review.

References

[1] Murray-Smith, D. (2019). *Powering Future Transport in Scotland*. A Technical Report for the Scottish Association for Public Transport, June 2019. Enlighten Publications, University of Glasgow. https://eprints.gla.ac.uk/189828/

[2] Murray-Smith, D. (2019) *A Review of Developments in Electrical Battery, Fuel Cell and Energy Recovery Systems for Railway Applications*. A Technical Report for the Scottish Association for Public Transport, November 2019. Enlighten Publications, University of Glasgow. https://eprints.gla.ac.uk/204435/

[3] Ghaviha, N., Campillo, J., Bohlin, M. et al. (2017). Review of application of energy storage devices in railway transportation. *Energy Procedia* 105, 4561–4568. https://reader.elsevier.com/reader/sd/pii/S1876610217310950?token=111C7C75FC66A169CA9760A5D80756E384D656670F1C65CB407BC63BFF8B751842C316B15EB1BEE02ABC29471AB3A397

[4] Liu, X. and Li, K. (2020). Energy storage devices in electrified railway systems: A review. *Transport Safety and Environment*, 2(3), 183-201. https://doi.org/10.1093/tse/tdaa016.

[5] Fidele, E., Iannuzi, D. and Del Pizzo, A. (2021). On board energy storage in rail transport: Review of real applications and techno-economic assessments. *IET Electrical Systems in Transportation*, 11(4), 279-309. https://doi.org/10.1049/els2.12026

[6] Saeed, M, Briz, F., Guerro, J.M. et al. (2023), Onboard energy storage systems for railway: Present and trends. *IEEE Open Journal of Industry Applications,* 4, 238-259. https://doi.org/10.1109/OJIA.2023.3293059

[7] Dominguez, M., Fernández-Cardador, A., Fernández-Rodríguez, A., et al. (2025). Review on the use of energy storage systems in railway applications, *Renewable and Sustainable Energy Reviews*, 207, 114904. https://doi.org/10.1016/j.rser.2024.114904 .

[8]Agarwal, A.K. and Biswas, S. (editors) (2025). *LCA and TEA for Sustainable Development*, Springer Nature, Singapore ISBN 978-981-96-6615-7 ISBN 978-981-96-6616-4 (eBook) https://doi.org/10.1007/978-981-96-6616-4.

[9] Hammond, J., Maher, B. A. Ahmed, I.A. et al. (2021). Variation in the concentration and regional distribution of magnetic nanoparticles in human brains, with and without Alzheimer's disease, from the UK. *Scientific Reports* 11, 9363. https://doi.org/10.1038/s45198-021-88725-3

[10] Statista – The Statistics Portal for Market Data. www.statista.com.

[11] Hasan, M.M., Haque, R., Jahirul, M.I. et al. (2025). Advancing energy storage: The future trajectory of lithium-ion battery technologies, *J. Energy Storage*, 120, 1-7, 116511. https://doi.org/10.1016/j.est.2025.116511
[12] de Bortoli, B., Rodrigues Camargo, M., de Oliveira Polkowski, R. et al. (2023). Graphene: an overview of technology in the electric vehicles of the future, SAE Technical Paper 2022-36-0100. Also, *Proceedings SAE BRASIL 2022 Congress,* ISSN 0148-7191. https://doi.org/10.4271/2022-36-0100.
[13] Zhang, N., Huang, Y., Fan, Y. et al. (2025). Learning from nature: Biomimicry in secondary batteries, *Materials Today*, 82, 223-250. https://doi.org/10.1016/j.mattod.2024.11.009.
[14] Abu Salem, K., Palaia, G. and Quarta, A. (2023). Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions. *Progress in Aerospace Sciences*, 141, 100924. https://doi.org/10.1016/j.paerosci.2023.100924.
[15] Ratniyomchai, T., Hellmannsen, S. and Tricoli, P. (2014). Recent developments and applications of energy storage devices in electrified railways. *IET Electrical Systems in Transportation.* 4(1), 9-20. https://doi.org/10.1049/iet-est.2013.0031 .
[16] Lee, J., Jung, M., Yun, S. et al. (2025). Safety analysis of thermal runaway in Lithium Titanate Oxide batteries under operational conditions, Scientific Reports 15(1), 31671 . https://doi.org/10.1038/s41598-025-16202-2.
[17] Meng D., Weng, J. and Wang, J. (2024). Experimental investigation of thermal runaway of lithium-ion batteries under low pressure and low temperature. *Batteries* 10(7), 243. https://doi.org/10.3390/batteries10070243.
[18] Zhang, Y., Tian, Z., Roberts, C. et al. (2022). Cost optimization of multi-mode train conversion for discontinuously electrified routes, *Int. J. Electr. Power Energy Syst*., 138, 107993. https://doi.org/10.1016/j.ijepes.2022.107993 .
[19] Abdurahman, B.M., Harrison, T., Ward, C.P. et al. (2021). An investigation into intermittent electrification strategies and an analysis of resulting CO2 emissions using a high fidelity train model. *Rail. Eng Science* 29, 314-326. https://doi.org/10.1007/s40534-021-00248-9.
[20] Abdurahman, B.M., Harrison, T., Ward, C.P. et al. (2023). Optimal intermittent electrification and its effect on battery sizing and energy saving using a high fidelity train model. *Proc. I. Mech E, Part F: J. Rail and Rapid Transit* 237, 9, 1205- 1218. https://doi.org/10.1177/09544097231159179.
[21] Ruvio,. A and Bayrak, O. (2024). A preliminary design of a hybrid train's on-board batteries for a 25kV-50Hz high speed railway line, *J. Energy Storage,* 84, Part B, 110966. https://doi.org/10.1016/j.est.2024.110966
[22] S. Shrestha, S. and Stuart-Smith, D. (2023). Partial electrification option for traction energy decarbonisation of an Australian railway. In CORE 2023: Conference on Railway Excellence. Celebrating 25 Years in Motion, pp. 82-93, Railway Technical Society of Australia, Melbourne, Australia. ISBN: 9781925627794.
[23] Murray-Smith, D. (2025). *An outline history of the Scottish battery electric train project 1955-66.* Technical Report, James Watt School of Engineering, University of Glasgow. September 2025. https://eprints.gla.ac.uk/365327/
[24] Heaton, J. (2024), Yellow Submarines, *The Railway Magazine,* 170, No. 1478, 38-43.
[25] Anonymous, Rail Business UK (2024). News item: Tri-mode trains launch South Wales Metro electric services, *Railway Gazette*, 27 November 2024, online. https://www.railwaygazette.com/uk/tri-mode-trains-launch-south-wales-metro-electric-services/67896.article
[26] Ford, R. (2024). News item: New trains – wanted or needed?, Table 6, *Modern Railways*, March 2024, p. 35.

[27] GOV.UK (2025). *ScotRail Suburban Fleet (EMU and BEMU) Market Engagement. Find a Tender*. www.find-tender.service.gov.uk.
[28] Anonymous (2025). *Fast charge battery technology: A viable option for regional rail?* Report, GWR Innovation. https://www.firstgroupplc.com/news-and-media/latest-news/2025/01072025.aspx .
[29] Anonymous (2025). News item: Siemens' new Rail Charging Converter a "gamechanger", *Rail,* 1039, 9-23 July 2025, pp. 8-9.
[30] Pilsner, P. (2025). Coventry (*very*) lights the way…., *Rail* 1039, 9-23 July, pp. 30-33.
[31] Anonymous (2019). News item: Schleswig-Holstein orders 55 battery-electric trains with Stadler. *Urban Transport Magazine*. 14.10.2019.
https://www.urban-transport-magazine.com/en/schleswig-holstein-orders-55-battery-electric-trains-with-stadler/
[32] Kaur, M. (2025). Siemens Mobility presents new battery trains for low-emission regional mobility, *Electric and Hybrid Rail Technology*, 21 July 2025. https://www.electricandhybridrail.com/content/news/siemens-mobility-presents-new-battery-trains-for-low-emission-regional-mobility
[33] Pedersen, K. (2025). Endangered species: Midtjyske Jernbaner Y-tog DMUs, *Today's Railways Europe,* Issue 354, August 2025, 32-35.
[34] Anonymous (2025). News item: More BEMUs for Lokaltog in Sjaeland, *Today's Railways Europe*, Issue 353, July 2025, p. 53.
[35] Anonymous (2024). News item: Hybrid *Régiolis* in service. *Today's Railways Europe*, Issue 342, August 2024. p. 46.
[36] Smith, K. (2024). News item: Trenitalia presents long-distance quadrupole-mode trains. *Int. Railway J.*, 6th April 2024, https://wwwrailjournal.com
[37] Anonymous (2024). News item: Hybrid *Régiolis* in service. *Today's Railways Europe*, Issue 342, August 2024. p. 46.
[38] Anonymous, Metro Report International (2024). First battery-electric train for Dublin's DART+ network unveiled, *Railway Gazette,* 7th May 2024, online.
https://www.railwaygazette.com/urban-rail/first-battery-electric-train-for-dublins-dart-network-unveiled/66471.article
[39] Anonymous (2024). News item: First DE 18 Smart Hybrid for Nexrail. *Today's Railways Europe*, Issue 336, February 2024, p. 11.
[40] Anonymous (2024). News item: Chicago orders battery *Flirts*. *Tramways and Urban Transit*, 1037, May 2024, p. 165.
[41] Anonymous (2020). *Unlocking new possibilities through innovative energy storage. The role of ultracapacitors in the energy transition*. An EIT Innoenergy White Paper in collaboration with Frost & Sullivan.
https://www.eit.europa.eu/sites/default/files/eitinnoenergy-frostsullivan_ultracapacitors_whitepaper_dec2020.pdf
[42] Partridge, J. and Abouelamaimen, D.I. (2019). The role of supercapacitors in regenerative braking systems, *Energies*, 12(14), 2683. https://doi.org/10.3390/en12142683.
[43] Mwambeleko, J.J. and Kulworawanichpong, T. (2021). Supercapacitors and accelerating contact lines hybrid tram system. *J. Energy Storage,* 44, Part A, 103277. https://doi.org/10.1016/j.est.2021.103277
[44] Wang, Y., Zhang, L. Hou, H., et al. (2021). Recent progress in carbon-based materials for supercapacitor electrodes, *J. Mater. Sci*., 56 pp.173-200. https://doi.org/10.1007/s10853-020-05157-6

[45] Zhang, J., Gu, M. and Chen, X. (2023). Supercapacitors for renewable energy applications: A review. *Micro and Nano Engineering* 21, 100229. https://doi.org/10.1016/j.mne.2023.100229
[46] Navarro, G., Torres, J., Blancu, M. et al. (2021). Present and future of supercapacitor technology applied to powertrains, renewable generation and grid connection applications. *Energies,* 14(11), 3060. https://doi.org/10.3390/en14113060
[47] Chen, J., Hu, H., Ge, Y., et al. (2020). An energy storage system for recycling regenerative braking energy in high-speed railway. *IEEE Trans. Power Deliv*., 36(1), 320-330. https://doi.org/10.1109/TPWRD.2020.2980018
[48] Kakati, D. and Ramadhas, A.S. (2025), A comprehensive review on lifetimes cycle assessment of hydrogen-powered internal combustion engine and fuel cell vehicle. In A.K. Agarwal and S. Biswas (eds.) (2025), *LCA and TEA for Sustainable Development*, Springer Nature, Singapore, Ch. 8, pp 189-219. ISBN 978-981-96-6615-7, ISBN 978-981-96-6616-4 (eBook}. https://doi.org/10.1007/978-981-96-6616-4_8.
[49] Islam, A., Shahriar, M.,. Islam Md. T. et al. (2025). Recent breakthroughs and future horizons in next-generation HT-PEMs for hydrogen fuel cell, *Int. J. Hydrogen Energy*, 168, 15113. https//doi.org/10.1016/j.ijhydene.2025.151113
[50] Dakal, T.C., Singh, N., Kaur, A. et al. (2025). New horizons in microbial fuel cell technology: Applications, challenges, and prospects, *Biotechnol. Biofuels Bioprod.*, 18, 79. Published online 18 July 2025. https://doi.org/10.1186/s13068-025-02649-y
[51] Singh, D. (2025). A review of hydrogen powered fuel cell vehicles: the present scenario and prospects for the future, *Current Sustainable/Renewable Energy Reports*, 12(1), 24 https://doi.org/10.1007/s40518-025-00270-z
[52] Wang, Y., Xu, C., Zhao, G. et al. (2025). Numerical simulation study on hydrogen leakage and explosion of hydrogen fuel cell buses, *Scientific Reports*, 15(1): 31976. https://doi.org/10.1038/s41598-025-17522-z.
[53] Shirres, D. and Baxter J. (2019). The future for hydrogen trains in the UK, Report, Institution of Mechanical Engineers, London. https://www.imeche.org/policy-andpress/reports/detail/the-future-for-hydrogen-trains-in-the-uk
[54] Various authors (2024). FCH_2RAIL Final Event presentation, Zaragoza, Spain, 26th November 2024. https://fch2rail.eu/project-results/fch2rail-final-event-presentation/
[55] Bu, Q., Sun, B, Yan, Y., et al. (2025). Parameter matching and real-time energy management for hydrogen hybrid power system for intercity electric multiple unit train. *Energy,* 336, 138293. https://doi.org/10.1016/j.energy.2025.138293
[56] Ding, D. and Liu, X.-Y. (2024). Hydrogen fuel cell electric trains: technologies, current status and future. *Applications in Energy and Combustion Science*, 17, 100255. .https://doi.o.Rrg/10.1016/j.jaecs.2024.100255 .
[57] Marjani, S. R., Motaman S., Varasteh H, et al. (2023), Assessing hydrogen as an alternative fuel for rail transport - a case study, *Scientific Reports*, 15 (1), 6449, https://doi.org/10.1038/s41598-1025-90887-3
[58] Sun, Y., Anwar, M., Hassam, N.M.S., et al. (2021), A review of hydrogen technologies and engineering solutions for railway vehicle design and operation. *Rail. Eng. Sci.* 29(3), 212-232. https://doi.org/10.1007/s40534-021-00257-8
[59] Peyrani, G., Marocco, P., Gandiglio, M., et al. (2025), Techno-economic modelling framework to assess the feasibility of hydrogen-powered trains on non-electrified routes *J. Power Sources*, 237677.
https://doi.org/ 10.1016/j.jpowsour.2025.237677
.[60] Correa, L. Razi, F., Sadiq, R. et al. (2024). Life cycle costing analysis of a retrofitted hydrogen-powered locomotive: Canadian context. *Transportation Research Part D: Transport and Environment,* 133, 104295.

https://doi.org/10.1016/j.trd.2024.104295.
[61] Ngadi,, A., Mesetlhe, T.C. and Yusuff, A. (2023), Advances in hydrogen-powered trains. A Brief Report, *Energies*, 16(18), 6715. https://doi.org/10.3390/en16186715
[62] Xu, L., Li, Y., Zhang, W., et al. (2025). Safety analysis of hydrogen-powered train in different application scenarios: A review. *Energies*, 18(7) 1743. https://doi.org/10.3390/en18071743
[63] Zhao, X., Wang, L., Zhou, Y., et al. (2022). Energy management strategies for fuel cell hybrid electric vehicles: Classification, comparison and outlook, *Energy Conversion and Management*, 270, 116179.
https://doi.org/10.1016/j.enconman.2022.116179
[64] Liu, S., Xu, C., Zhang, Y. et al. (2024), Multiobjective parameter configuration optimization of hydrogen fuel cell hybrid power system for locomotives. *Electronics* 13(8), 3599. https://doi.org/10.3390/electronics13183599.
[65] Ding, Y., Peng, Y., Huang Y., et al. (2024), Energy-efficient train control considering on-board energy storage based on convex optimization. *Int J. Rail Transportation.* 1-29. https://doi.org/10.1080/23248378.2025.2529403
[66] Anonymous (2025). News item: "It makes sense to do hydrogen trains on the right routes", says Lhyfe. *Railway Gazette.* Online, 21st May 2025.
https://www.railwaygazette.com/traction-and-rolling-stock/it-makes-sense-to-do-hydrogen-trains-on-the-right-routes-says-lhyfe/68836.article
[67] Anonymous. HydroFLEX is the UK's first hydrogen-ready passenger train. Online access. https://www.porterbrook.co.uk/innovation/hydroflex-cop
[68] Calvert C., Allan, J., Amor P., et al. (2021), Concept development and testing of the UK's first hydrogen-hybrid train (HydroFLEX), *Railway Engineering Science,* 29(3), 248-257. https://doi.org/10.1007/s40534-021-00256-9
[69] Xu, Z., Zhao, N., Hillmansen, S., Roberts, C. et al.. (2022). Techno-economic analysis of hydrogen storage technologies for railway engineering: A review. *Energies*, 15 (17), 6467. https://doi.org/10.3390/en15176467
[70] Anonymous, Rail Business UK (2025). News item: HydroShunter demonstrator loco unveiled. *Railway Gazette*. 5th February 2025. Online.
https://www.railwaygazette.com/uk/hydroshunter-demonstrator-loco-unveiled/68257.article
[71] Anonymous (2024). News item: Steam power 'Tug' for freight trains. *The Railway Magazine*, 170, No.1480, July 2024, p. 11.
[72] Anonymous (2025). News item: Bagnères-de-Luchon line reopens. *Today's Railways Europe,* Issue 354, August 2025, p. 44.
[73] Anonymous (2024). News item: 'End-to-end' hydrogen co-operation accord. *Railway Gazette.* 27th June 2024. Online,. https://www.railwaygazette.com/traction-and-rolling-stock/end-to-end-hydrogen-co-operation-accord/66805.article
[74] Simmons, M. (2024). Talgo to co-develop hydrogen-powered high-speed train. *International Railway Journal*, 23rd January 2024. Online.
https://www.railjournal.com/passenger/high-speed/talgo-to-co-develop-hydrogen-powered-high-speed-train/
[75] Bent, M. (2023). TRAKO 2023. New stock on show in Gdansk. *Today's Railways Europe*, Issue 334, December 2023, pp. 14-15.
[76] Anonymous (2023). News item: 071 Class hydrogen trial, *Today's Railways Europe*, Issue 333, November 2023, p. 53.
[77] Anonymous (2024), News item: Hydrogen tram for Gōrlitz, *Today's Railways Europe*, Issue 338, April 2024, p. 10.

[78] Anonymous (2025). News item: China – first hydrogen locomotive starts trial commercial operation. *Hydrogen Central* website. https://hydrogen-central.com/china-first-hydrogen-locomotive-starts-trial-commercial-operation/
[79] Anonymous (2024). News item: World's first hydrogen-powered tram service suspended amid rising costs: report. *Hydrogen Insight* website. 6th September 2024. https://www.hydrogeninsight.com/transport/world-s-first-hydrogen-powered-tram-service-suspended-amid-rising-costs-report/2-1-1705590
[80] Anonymous (2024). News item: More on hydrogen fuel cell tram by Hyundai Rotem. *Rolling Stock World* website. 23rd September 2024. Online. https://rollingstockworld.com/lrv/more-on-hydrogen-fuel-cell-tram-by-hyundai-rotem/
[81] Anonymous (2025). News item: California's Hydrogen Rail Revolution: Stadler FLIRT H2 Expands. *Railway News* website, 1st April 2025. Online. https://www.railwaynews.net/californias-hydrogen-rail-revolution-stadler-flirt-h2-expands.html
[82] Madovi, O., Hoffrichter, A., Little, N., et al. (2021). Feasibility of hydrogen fuel cell technology for railway intercity services: a case study for the Piedmont in North Carolina (2021). *Rail Eng. Sci.* 29, 258-270. https://doi.org/10.1007/s40534-021-00249-8
[83] Oldknow, K., Mulligan, K.K. and McTaggart-Cowan, G. (2021). The trajectory of hybrid and hydrogen technologies in North American heavy haul operations. *Rail Eng. Sci.* 2021 29, 233-247. https://doi.org/10.1007/s40534-021-00242-1.
[84] Norman, H. (2022), News item: Wabtec Corporation kicks off hydrogen research project, *Electric and Hybrid Rail Technology.*10 Nov. 2022. Online. https://www.electricandhybridrail.com/search?query=Wabtec+Corporation+kicks+off+hydrogen+research+project%2C+Electric+and+Hybrid+Rail+Technology.10+Nov.+2022.
[85] Khan, T. and Shao, Z. (2024), Zero-emission locomotive technologies: Pathways to US rail decarbonization, International Council for Clean Transportation, Technical Brief, June 27 2024. https://theicct.org/publication/zero-emission-locomotive-technologies-pathways-for-u-s-rail-decarbonization-jun24/
[86] Knibbe, R., Harding, D., Burton, J., et al. (2023). Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives, *J. Energy Storage,* 71, 108090. https://doi.org/10.1016/j.est.2023.108090
[87] Cole, C., Sun, Y., Wu, Q. et al. (2023). Exploring hydrogen fuel cell and battery freight locomotive options using train dynamics simulation. *Proc. I. Mech. E. Part F, J. Rail and Rapid Transit.* 238(3), 310-321. https://doi.org/10.1177/09514097231166477/.
[88] Adetokun, B.B., Oghorada, O., and Abubakar, S.J. (2022), Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications. *Journal of Energy Storage*, 55, Part C, 105663. https://doi.org/10.1016/j.est.2022.105663
[89] Salama, H.S. and Vokony, I. (2020), Comparison of different electric vehicle integration approaches in presence of photovoltaic and superconducting magnetic energy storage systems. *Journal of Cleaner Production,* 260, 121099. https://doi.org/10.1016/j.jclepro.2020.121099
[90] Yang, B., Zhu, T., Zhang, X, Wang, J. et al. (2020). Design and implementation of Battery/SMES hybrid energy storage systems used in electric vehicles: A nonlinear robust fractional-order control approach. *Energy,* 191, 116510. https://doi.org/10.1016/j.jenergy.2019.116510
[91] Wei, C., Undavalli, V.K., Perkins, C. et al. (2025). Technical and economic assessment of cryogenic fuels for future aviation. *Progress in Aerospace Sciences,* 153, 101053. https://doi.org/10.1016/j.paerosci.2024.101053

[92] Shen, B., Chen, Y. Fu, L. et al. (2023), Superconducting magnetic energy storage (SMES) for urban railway transportation. *2023 IEEE Int. Conf. on Applied Superconductivity and Electromagnetic Devices*, 21-23 October 2023, Tianjin, China. https://doi.org/10.1109/TASC.2024.3400670
[93] Li X. and Palazzolo, A. (2022). A review of flywheel energy storage systems: state of the art and opportunities, *J. Energy Storage*, 46, 103576 https://doi.org/10.1016/j.est.2021.103576
[94] Xu, K., Guo, Y., Lei, G. et al. (2023), A review of flywheel energy storage system technologies, *Energies*, 16(18) 6462. https://doi.org/10.3990/en16186462.
[95] Choudhury, S. (2021), Flywheel energy storage system: a critical review of technologies, applications, and future prospects, *Int. Trans. Elect. Energy Syst.*, 31(9), e13024. https://doi.org/10.1002/2050-7038.13024.
[96] Jackiewicz, J. (2023), A flywheel-based regenerative braking system for railway vehicles, *Acta Mechanica et Automatica,* 17(1), 52-59. https://doi.org/10.2478/ana-2023-0006.
[97] Khodaparastan, M. (2020), *Recuperation of regenerative braking energy in electric rail transit systems*, City University of New York, PhD Dissertation, 2020.
[98] Various authors (2020). *Digital Displacement for Non-Passenger Rail (COF-IPS-03)*. Final Report. Rail Safety and Standards Board.18th June 2020. Online. https://docslib.org/doc/697633/cof-ips-03-digital-displacement-for-non-passenger-rail
[99] Murray-Smith, D.J. (2018). Development of an inverse simulation method for the analysis of train performance. *Proceedings of the Institution of Mechanical Engineers. Part F: Journal of Rail and Rapid Transit*, 232(5), 1295-1308. (doi: 10.1177/0954409717720349)
[100] Murray-Smith, David (2020). *Modelling and simulation of hybrid electric trains powered by hydrogen fuel cells and batteries for routes in the highlands of Scotland. Preliminary results.* A report for the Scottish Association for Public Transport. Technical Report. James Watt School of Engineering, University of Glasgow, 27 June 2020. http://eprints.gla.ac.uk/222731/1/219364.pdf
[101] Murray-Smith, David (2020) *Design Options for Hybrid Trains Powered by Hydrogen Fuel Cells and Batteries for Routes in the Highlands of Scotland. Results for the case of a three-coach multiple-unit train.* A report for the Scottish Association for Public Transport. Technical Report. James Watt School of Engineering, University of Glasgow, 27th August 2020. http://eprints.gla.ac.uk/222731/1/222731.pdf
[102] Chen, Z., Wu, X., Moo, J. et al. (2025). Hierarchical energy management strategy for dual fuel cell systems in heavy-duty trucks based on multi-objective optimisation. *Energy Convers. Management*, 345, 120308. https://doi.org/10.1016/j.enconman.2025.120308
[103] Deng, K., Fang, T,. Feng, H. et al. (2022) Hierarchical eco-driving and energy management control for hydrogen-powered hybrid trains, *Energy Convers. Management,* 264 (2) 115735. https://doi.org/10.1016/j.enconman.2022.115735
[104] Kapetanović, M., Núñez, A., Van Oort, N. et al. (2022). Analysis of hydrogen-powered propulsion system alternatives for diesel-electric regional trains, *J. Rail Transp. Planning Manag,* 23, 100338. https://doi.org/10.1016/j.jrtpm.2022.100338
[105] Zhang, Y., Yu, J., Zhao, N. et al. (2024), Particle swarm optimization for a hybrid freight train powered by hydrogen or ammonia solid oxide fuel cells, *Int. J. Hydrogen Energy,* 72, 626-641. https://doi.org/10.1016/j.ijhydene.2024.05.347
[106] Cäsar, J., Shamiyeh, M., Weintraub, D. et al. (2025). Integrated preliminary design of fuel cell propulsion systems for vertical take-off aircraft. *CEAS Aeronautical Journal*, Published online 14 July 2025, https://doi.org/10.1007/s13272-025-00873-8.

[107] Wilcock, R. (2024). Battery trains 'could save the UK rail network £3.5 billion'. *Rail*, 6th June 2024. Online. https://www.railmagazine.com/news/2024/06/06/battery-trains-could-save-the-uk-rail-network-35-billion-claim-siemens-mobility
[108] Anonymous (2025). News item: Turntide to supply advanced LFP batteries for UK battery trains. *Railway Technology* 2nd July 2025. Online. https://www.railway-technology.com/news/turntide-advanced-lfp-batteries-uk-first-battery-trains/
[109] Smith, K. (2023). LNER orders 10 tri-mode trains from CAF. *International Railway Journal*, 9th November 2023. Online. https://www.railjournal.com/passenger/main-line/lner-orders-10-tri-mode-trains-from-caf/
[110] Abbott, J., (2025). GWR focuses on regional fleet. *Modern Railways*, September 2025, pp. 58-63.
[111] Anonymous (2024). News item: Siemens' British battery trains set to save £3.5Bn and consign diesel trains to history. Siemens website. https://news.siemens.co.uk/news/siemens-british-battery-trains-set-to-save-gbp-3-5bn-and-consign-diesel-trains-to-history?linkId=300000011807693
[112] Pickering, G. (2024). Clayton's Class 18 hybrid loco fleet is ready for use, *The Railway Magazine,* 170, No. 1474, January 2024, p. 11.
[113]Anonymous, Rail Business UK (2020). Hybrid shunter conversion ready for testing, *Railway Gazette*, online 8th May 2020. https://www.railwaygazette.com/uk/hybrid-shunter-conversion-ready-for-testing/56472.article
[114] Anonymous (2025). News item: Heidelberg orders battery 08e. *Modern Railways Online*, 23rd January 2025. https://www.modernrailways.com/article/heidelberg-orders-battery-08e
[115] Anonymous. *About Coventry Very Light Rail*. Coventry City Council website. https://www.coventry.gov.uk/coventry-light-rail/light-rail
[116] Anonymous (2024). News item: Very Light Rail for Heathfield branch? *Modern Railways*, May 2024, p. 15.
[117] Miles, T. (2024). Battery train for Dublin unveiled, *Modern Railways*, June 2024, pp. 82-83. Ireland
[118] Anonymous (2024). News item: New BEMU to start testing in September. *The Railway Magazine*, 170, No. 1479, June 2024, p. 105.
[119] Pulling, N. (2024). Systems Factfile No.196, Granada, Spain. *Tramways and Urban Transit*, 1034, February 2024, pp. 66-70.
[120] News item (2020), *Scottish Enterprise website* (2020) Hydrogen train project looks back to the future https://www.scottish-enterprise-mediacentre.com/news/hydrogen-train-project-looks-back-to-the-future
[121] Press release (2021), *H_2A Hydrogen Accelerator website, University of St Andrews*, Zero emissions train project https://h2-accelerator.org/projects/train
[122] Rail Business UK, (2022) Scottish hydrogen train testing completed. *Railway Gazette International* 12/10/2022 https://www.railwaygazette.com/uk/scottish-hydrogen-train-testing-completed/62742.article
[123] Murray-Smith, David J. and Fisher, Peter (2021), *Hybrid trains for the Highlands? Computer Simulations of Fuel-cell/Battery-electric Trains on Secondary Routes in Scotland.* A Progress Report on an Industry and University Collaboration. Technical Report. James Watt School of Engineering, University of Glasgow. phttps://eprints.gla.ac.uk/251312/1/251312.pdf
[124] Clinnick, R. (2025), Class 99. The future of rail freight, *Modern Railways* , April 2025, pp. 64-69.
[125] Anonymous (2024). News item: Tests show hydrogen generator cleans up diesel emissions. *Rail*, 1012, June 26th -July 9th 2024, p. 15.

[126] P. Dunn, Steam-powered Class 60 planned for short-haul freight, *Rail*, 1012, 26th June-9th July 2024, pp. 8-9.
[127] Anonymous (2024), News item: Steam power for Class 60, *Modern Railways*, July 2024, p. 20.
[128] Fritz-Bleeck, N. (2025). Siemens Mobility Mireo Plus H begins regular service in Germany- powered by Ballard. Ballard Power systems website. February 1st 2025. https://blog.ballard.com/rail/siemens-mobility-mireo-plus-h-begins-operation-germany
[129] Anonymous (2024). News item: Arriva halts hydrogen train tender. *Today's Railways Europe*, Issue 337, March 2024, p. 46
[130] Anonymous (2025). News item: Prototype hydrogen shunting locomotive unveiled. *Railway Gazette*, 26 June 2025. Online. https://www.railwaygazette.com/traction-and-rolling-stock/prototype-hydrogen-shunting-locomotive-unveiled/68898.article
[131Anonymous (2025): News item: India made hydrogen fuel train engine more powerful than others: Ashwini Vaishnaw. *Economic Times*, English Edition. 9th January 2025New Delhi, India. https://economictimes.indiatimes.com/industry/transportation/railways/india-made-hydrogen-fuel-train-engine-more-powerful-than-others-ashwini-vaishnaw/articleshow/117092867
[132] Anonymous (2025). News item: Overhead-free in South Korea, *Tramways and Urban Transit*, 1051, July 2025, p. 25